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Quieter Gears Are Being Demanded! How Shall We Make Them?

By Fred W. Cederleaf
General Superintendent of Non-Productive, Olds Motor Works

LIMITATIONS of present processes for cutting and finishing transmission gears are covered in a general way by Mr. Cederleaf. He shows also that future demands for more quiet transmissions can be met only by an equal improvement in gear-cutting-and-finishing equipment; or by the development of new processes; or by the realization, on the part of engineers, that the most economical method of obtaining better results is, by redesign, to eliminate from the transmission the necessity for greater dimensional accuracy.

DURING the last four years my work has taken me into many transmission plants and departments. These visits have disclosed the fact that although everyone was striving for the same goal, namely, the production of a quiet and durable gearset at an economical cost, the materials and methods used in an attempt to accomplish this task varied greatly.

The glorious introduction to the general public of the helical-gear transmissions in the year 1930 by our ambitious advertising managers, who flashed the words "silent second" from coast to coast, will long be remembered by the man whose job it was to make these gears "silent," and after three years of hard work the best that has been accomplished is that, although not "silent," they are at least "more quiet" than their predecessors, namely, spur gears.

During these three years, plants have been rearranged, personnel reorganized, millions of dollars of new equipment purchased, designs changed, and new processes have come and gone; all in an attempt to meet that demand for more quiet gears.

Much has been accomplished; nevertheless, this accomplishment seems rather small when contrasted with the amount of energy and money expended.

[This paper was presented at the International Automotive Engineering Congress, Chicago, Aug. 29, 1933.]

In an attempt some time ago to find the answer to whether or not it is possible that the standard of quietness demanded requires accuracy beyond the capacity of available equipment, our company had ten sets of helical gears ground to master-gear tolerances; namely, to an accuracy of ± 0.0002 in. on tooth profile, spacing, spiral angle and concentricity. After these gears were checked, they were assembled into ten transmission cases that also had been checked to assure that all dimensions were to drawing tolerances, and then installed in cars and driven. Six of these gearsets were passed as being satisfactory; the other four were rejected as being too noisy.

At that time, various reasons were given for these failures. Although the accuracy of the center distances in the cases assured alignment of the second-speed gear with its mating gear on the cluster, any out-of-squareness of the clutch-housing face or misalignment of the bearing pocket would cause the drive gear to operate on a different axis from that on which it was ground. However, the test did prove that master-gear accuracy is desirable, if not absolutely essential, for the manufacture of interchangeable transmission gears. Modification of tooth profiles, combination of pitches, position of the gears in the case, may all have a bearing on final results; but none of these factors seems to affect the degree of noise so much as do errors of tooth profile, spacing, and concentricity.

Although methods vary considerably in transmission plants, in the processing of helical gears there are really only two distinct classifications: grinders and non-grinders. Of the eleven transmission plants studied, two of them process to grind gear teeth after hardening, while the other nine process to avoid the necessity for this operation. I do not know of any other hardened part of an automobile, which must be held to such close tolerances, that is not ground after heat treatment. Camshafts, valves, ball and roller bearings, overrunning cams, rollers and the like, are all ground after hardening in all plants that manufacture them.

No doubt the grinder-equipment companies have asked many times why every gear manufacturer does not grind gears and have received many different answers. When we read some of the claims made by some gear-tooth-grinder

"Have we reached the limit of accuracy obtainable with present processes?"

"Will present gear-equipment manufacturers keep up with the higher standards of accuracy required, or will new processes render the old processes obsolete?"

"Why doesn't every gear manufacturer grind gears?"

These are some of the questions asked by Mr. Cederleaf, who goes into detail in answering them.

manufacturers in reference to their process, we wonder still more why every plant does not standardize on this method and quit trying to be different. A paragraph that I copied from one gear-tooth-grinder circular reads:

"A summary of the foregoing comparison is 83 1/3 per cent less idle machine time, 80 per cent less labor cost and 76 per cent less wheel cost in favor of the rack-tooth wheel. Is it any wonder we are enthusiastic about it, when it, in connection with our grinder, makes it possible to reduce the production cost of the *ground* gear to *less* than that of the unground gear?"

Another paragraph reads:

"The production of quiet, long-wearing, automotive-transmission gears and other precision gears, is a problem that has long perplexed gear engineers. This is particularly true of heat-treated and hardened gears, where fire distortion and warpage frequently destroy the preliminary precision-machining efforts. Gears in modern machinery require extreme precision to assure quiet-running qualities and necessary strength, and these results can be obtained in one way only—by grinding the teeth on our gear grinder after hardening. When all of the related elements and factors are properly considered, a tooth-grinding operation is no more expensive than other methods of attempting to obtain close accuracy and fine finish."

Considering all this, no doubt we would all be grinding gear teeth if it were not for a group of production men that are always trying to do the impossible and sometimes succeed.

The two plants mentioned, that use a grinding operation for finishing the teeth after hardening, process their gears more or less alike. In one case, S.A.E. 2315A steel is used; and, in the other case, S.A.E. 5140A steel. In both cases, one hobbing cut only is used on teeth holding tolerances of about ± 0.001 in. for contour, spacing, lead and concentricity, 0.002 to 0.005 in. of stock being allowed on the tooth face for grinding.

After gears are hardened, they are chucked in "pitch-line" chucks and the inside diameters are ground or "diamond-bored," depending on the type of bearing used. A mandrel is then pressed into this ground or bored hole, and the teeth are ground concentric with the bore. Two types of grinders are used in these plants. One uses a rack-tooth wheel on a reciprocating ram, which traverses the work and indexes at the end of each stroke. The other machine generates an involute curve by rotating and reciprocatingly traversing the work under and back of the flat side of a dish-shaped wheel. In the hands of a skilled operator, each of these grinders is capable of finishing gears to master-gear accuracy. In fact, master-gear makers use both types of grinders for finishing their product.

As mentioned previously, master-gear tolerances are ± 0.0002 in. on tooth profile, spacing, spiral angle and concentricity. To produce work to this accuracy, the master-gear manufacturer finds it necessary to charge approximately $50 for each gear. Most of this cost covers the skilled grinding-operator's time on the very same gear-tooth grinders that are being used in the two transmission plants mentioned. It is needless to say that $50 per gear would be prohibitive for use in a production transmission.

I have also stated previously that master-gear tolerances are desirable if not absolutely necessary to produce gears which will function to the satisfaction of the present-day demand. What is the answer? The answer is trouble and grief. When you substitute a 65 cents-per-hr. man for the skilled mechanic, when you reduce grinding time allowed from hours to minutes, and when you have to produce a complete transmission for less than the cost of one master gear, you will naturally try to find short cuts. The short cuts attempted are to accept more errors from the gear-tooth grinders; then, after grinding, to lap the gears by various lapping methods and, finally, to use a selective assembly by sound-testing the mating gears on matching machines.

Further Improvements Difficult

In emphasizing again the purpose of this paper, it is not my intention to criticize or find fault with any method used to cut or finish gears. What I am trying to show is that all of us have just about reached the limit of results with the tools that are available, and that, unless the machine-tool builders have something new to show us, we production men would like to put this job back in the laps of the engineers that are responsible for transmission design with the hope that they will see the picture as we see it and that they will not demand more quiet transmissions until they find a way to use gears produced to tolerances comparable with other parts of an automobile.

Let us now leave the transmission plants that use gear-tooth grinders for finishing and look into the methods used by the nine others who are attempting other processes to produce the same results at less cost.

Finished-gear accuracy without grinding is dependent on three factors:

(1) Extent of errors of tooth profile, spacing, concentricity and lead after hobbing, shaping, burnishing, or shaving, before the gear is hardened

(2) Amount of fire distortion and the ability to anticipate and allow for this change

(3) Method used to remove accumulative errors after hardening

There seems to be quite a difference of opinion as to the best material to use, as we find in these nine cases everything from the 3 and the 5-per cent low-carbon carburizing-series to the straight oil-hardening carbon-chromium steels containing from 45 to 60-per cent carbon. Some of the latter steels are brought up to heat in cyanide baths, while others use "aero case." Entire papers have been devoted to the merits of these steels for transmission gears, and there is still a question as

to just which physical properties have the greatest bearing on gear life.

Considering the fact that all of these nine "non-grinder" processes have for their goal the same objective, namely, to send to the fire a gear as nearly perfect as possible, the methods used vary considerably. One concern first rough-hobs the teeth with double and triple-thread unground-hobs, then finish-cuts on gear shapers, after which the gear is given a burnish to smooth out cutter marks. Another plant first rough-hobs and then finish-hobs and burnishes. Another single-cuts the teeth in a hobbing machine with a ground hob, and light burnishes. Another method used is to single-cut with an unground hob in a rotary multi-spindled hobbing-machine, then to remove from 0.003 to 0.005 in. of stock on a shaving machine, and then to light burnish. All these concerns have found it necessary to install gear laboratories containing instruments for checking the work from each operation. The standard of measurement is 0.0001 in.

Much can be said regarding the measurements and limitations of these different processes, but the best results obtainable are not good enough to produce gears, which, after hardening, can be assembled into satisfactory transmissions without corrective measures being taken.

Cutting

Some of these processes produce a gear that, before hardening, checks surprisingly close to master-gear accuracy, but the pressure exerted by the cutting and burnishing tools used to produce this result sets up strains on the surface of the tooth. These strains are released in the heat-treating operation, causing errors which necessitate a corrective operation before the gear can be used in a transmission.

The ideal process would be one that would produce perfect contours, spacing, leads and concentricity, without setting up any surface strains, inasmuch as any available after-hardening corrective means, aside from grinders, is capable only of taking care of the regular fire changes which take place.

Such a process has not yet been developed; at least, I know of none. To hold limits of 0.0005 in. on contours, spacing, lead and concentricity on gears before hardening, whether you use hobbing machines or shapers, requires more supervision, checking and maintenance, than on any other part used in an automobile. Passable results can be obtained only by being eternally vigilant.

Fire Changes

To produce satisfactory transmission gears without grinding, the following procedure is necessary:

(1) Steel must be purchased from mills that have equipment and organization and a personnel that can and will produce material that is within the limits of analysis and specifications, consistently.

(2) The forging source must produce forgings having uniform density of structure.

Unless steel is uniform, forgings cannot be uniform. Unless forgings are uniform, the normalizing cycle cannot be regulated to produce uniform structure. Without uniform structure, it is impossible to eliminate or anticipate fire changes. Without knowing how gears are going to change in the hardening operations, allowance cannot be made for these changes and, if the changes are not allowed for, the error in the hardened gear will be too great to remove except by grinding.

Fire changes of tooth profile vary from 0.0002 to 0.0005 in. Hobs and gear-shaper cutters can be obtained easily to produce a tooth profile with allowance for this change of contour in hardening, as these tools are manufactured consistently to within 0.0002-in. accuracy. The difficult part is to know what change to allow for.

It is only by having a uniform forging and a uniform fire change that advantage can be taken and proper allowances made. Ordinary commercial forgings vary too much in structure and, likewise, vary considerably in heat-treatment distortion. The more uniform the results obtained after hardening are, the better the opportunity is to measure and allow for change.

As an example of how difficult it is to get any kind of a picture of so-called commercial-forging fire-change, I know of a case in which one man was given the job of checking gears daily before and after hardening for the purpose of using the data obtained for making necessary allowances on the hobs. He actually worked on this job one whole year without any results, due to the fact that the data obtained one week were rendered useless the next week by the inconsistency of the results.

By uniform structure in forgings, I mean forgings made from steel of a definite grain-size, forged at a controlled temperature in dies designed so that the full pressure of the forging-machine ram is used to compress the forging itself and is not wasted on trying to compress a cold flash. This method produces a so-called "dense" forging, which, in both normalizing and the hardening cycle, absorbs and dissipates heat at a uniform and measurable degree.

This whole paper could be devoted to the importance of structure of forgings to produce transmission gears without grinding, but the metallurgical-research details that have been carried out on this project can be obtained elsewhere.

"The ideal gear-cutting process would be one that would produce perfect contours, spacing, leads and concentricity, without setting up any surface strains, inasmuch as any available after-hardening corrective means, aside from grinders, is capable only of taking care of the regular fire changes which take place. Such a process has not yet been developed; at least, I know of none.

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Although accuracy in cutting and chucking is reflected in wheel cost by the "grinding" process, good gears can still be made by this method, even though poorly cut and eccentric. But the "lapping" process requires gears to come to the lapping machines with contours, spacing and concentricity with less than a 0.001-in. error. For this reason, former practices of gang cutting and pitch-line chucking cannot be used with this process; in their place, centers must be used wherever possible.

Assuming that gears must run conjugately within from 0.0002 to 0.0005 in. to pass the present-day standard satisfactorily, and assuming that the greatest error that can be corrected economically by the lapping process is 0.001 in., and realizing that the best chucking and cutting must have some allowances and also that some changes in hardening aside from what can be allowed for must creep in, it is obvious that I must be making misstatements somewhere along the line. So, let us review the situation to see what is wrong.

Medium-sized gears, when produced from uniform-structure forgings such as described, will shrink or expand in the hardening operation within a total variation of approximately 0.002 in. on pitch diameter as measured over pins. The spacing and contour change should not exceed 0.001 in., of which, if proper data are obtained, one-half of this error can be allowed for. The 0.002-in. variation in pitch diameter is not so serious in an involute gear, as this affects backlash only, the tooth profiles still remaining conjugate.

Errors in cutting directly chargeable to the gear-tooth-cutting machine vary according to the method used and also according to the condition of the machine.

Table 1—Grinding Versus Non-Grinding Cost-Comparison

	Grinding Process	Lapping Process	Savings Per Set	Savings Per Year
Operations Compared	Grind, Lap and Match	Burnish, Lap and Match	....	....
Kind of Equipment Used	Gear-Tooth Grinders Lappers Matchers	Burnishers Lappers Matchers	....	....
Number of Machines Required for the Production of 30 Gearsets per Hr.	Grinders, 37 Lappers, 4 Matchers, 2	Burnishers, 4 Lappers, 12 Matchers, 2	....	....
Total Cost of Equipment	$285,134	$34,950	....	....
Machine Depreciation per Gearset, Based on a Yearly Production of 72,500	$0.393	$0.048	....	....
Labor Cost per Set:				
Grinding,	$0.325	$0.000		
Burnishing,	0.000	0.022		
Lapping,	0.036	0.043	....	....
Matching,	0.021	0.048		
Total	$0.382	$0.113		
Grinder Wheel Cost per Set, Grinding Process	$0.082	$0.000	....	....
Lap and Burnisher Cost per Set, Non-Grinding Process	$0.000	Laps, $0.010 Burnishers, 0.012 Total $0.022	....	....
Balance of Burden; 150.7 Per Cent of Production Labor (Standard Burden Less Machine Depreciation and Perishable-Tool Cost	$0.575	$0.170	....	....
Total Factory Cost Per Set for Operations Listed	$1.432	$0.353	$1.079	$78,227.50
Factory Cost Plus 30 Per Cent Yearly Return on Investment	$2.611	$0.497	$2.114	$153,265.00
Factory Cost Plus 6 Per Cent Yearly Return on Investment	$1.668	$0.381	$1.287	$93,307.50

Hobbing-Machine Results

A well-known hobbing-machine manufacturer built a machine a few years ago, incorporating the most accurate parts obtainable for the purpose of finding out just how accurately gears could be cut by this method. The following is his company's report on the results:

"We believe the machine as sent you will give as nearly accurate results as can be obtained in a production machine. In other words we are able, with this type of machine, when cutting your gears, to hold indexing to within 0.0005 in. We also feel we must call your attention to the fact that, in order to produce the results obtained as above noted, your operators must take particular care to keep the machine in as perfect condition as possible. For instance, we are running the worm and worm gear with as little backlash as possible and still be able to keep this unit from heating excessively due to friction. Every point on this machine must be kept in this same relationship, if you are to secure the proper results."

Although this particular test was made on a hobbing machine, I believe that the same requirements, so far as keeping the working parts of the machine in perfect condition, applies also to any other of the present type of gear-cutting equipment. The errors in ground hobs, shaper cutters and shaving racks do not exceed 0.0002 to 0.0003 in. The errors in chucking vary in different plants, but the best methods still allow the gears to be eccentric from 0.001 to 0.002 in. If, therefore, we add the errors of fire change, gear-tooth cutting and chucking, even from the best practice, we will have a total error in excess of the amount that should be removed by a lapping operation.

The facts of the matter are that the manufacturers that produce helical-gear transmissions without grinding do not and cannot produce consistently gears having master-gear accuracy. Nevertheless they keep trying and, with the help of selective assembly and constant inspection and checking, the finished gearset is just about equal in quietness and performance to the production-ground job.

In the past we have generally found that, the longer we work on a process, the better the results obtained are; but, when we consider that machines must wear and get out of adjustment,

that cutting tools do get dull and that fixtures change in time, you will get some idea of why I say: "Quieter gears are demanded! How shall we make them?"

If it were not for just one thing, cost, the answer to that question no doubt would be "grind them!" I have been fortunate in obtaining permission to outline here the difference in cost between the grinding process and the non-grinding process as applied to finishing helical gears, which data were compiled from records covering two years' production with each of these methods. The comparison is made in Table 1, on the basis of an equipment capacity of 30 gearsets per hr.

The gearset to which this analysis applies is used in a transmission containing helical gears having a total of 78 teeth. Without considering the "return-on-the-investment" factor, the cost of the grinding method amounts to about 1 1/3 cents per tooth more than that of the lapping method.

Although our 37 gear-tooth grinders occupy more floor space and also require more supervision than do our 12 lapping machines, no additional cost has been added, as this extra expense is just about offset by the extra supervision and floor space necessary in the gear laboratory and hobbing department to assure the more accurate cutting required for the lapping method.

The lapping method requires forgings of uniform structure to assure uniform fire change; but the extra cost, if any, for accomplishing this, is offset by the savings derived from the faster feeds and speeds that this type of forging permits. Incidentally, this new type of forging has reduced the grinding cost on the gear teeth materially, as less fire distortion makes it possible to leave less stock for grinding. Last year, the gear-tooth-grinding department carried 11 non-productive men, while today there are none, even the foreman being in the group.

The "grinding process," referred to in this analysis, incorporated the following operations:

(1) Single-cut the gear teeth on a hobbing machine
(2) Grind the teeth on gear grinders
(3) Lap the teeth on lapping machines, in sets
(4) Match the gears on matching machines when necessary

The "lapping process," referred to in this analysis, incorporates the following operations:

(1) Single-cut the gear teeth on a hobbing machine
(2) Green-burnish them on burnishing machines
(3) Lap the teeth on lapping machines, singly
(4) Match the gear on matching machines.

Gear-Tooth-Grinding Data

Tolerances.—The tooth spacing averages 0.0002 to 0.0003 in., using single index on the grinder. The involute is held to ± 0.0002 in. The backlash is 0.002 to 0.004 in.

Cutting.—The rough-cut index per tooth is 0 deg. 9 sec. when running single index. For double index, 19 to 20 strokes of the ram per tooth are made and, for the finish cut, the ram makes 20 strokes per 1 in. of table travel.

The only gears run on single index are the 24 and 27-tooth counter-gears.

A Norton 3850 K5B 12-in.-diameter wheel is used, at a speed of 2400 r.p.m. After the wheel is reduced in size to 11 in. in diameter it is transferred to a grinder having a spindle speed of 2650 r.p.m.

New wheels are used on counter gears; small wheels, on second-speed and on clutch gears.

All grinders are run empty for 2 hr. daily to get all parts of the machine to a balanced temperature before starting production.

Wheels cost approximately \$2.28 each and will average 2000 teeth per life of the wheel, or \$0.0011 per tooth.

One man runs 3½ machines, excepting the man who rolls gears to test for low teeth. He runs two machines in addition to rolling gears for all machines.

The day crew of eight operators, of whom one is group leader, one a wheel man and one an involute checker for 35 grinders, plus the night crew of three men, all of whom are operators, will complete 14½ transmission sets per hr. or 235 jobs per day of 11 hr. per man.

Each gear receives three grinder cuts, two rough and one finishing revolution.

Tolerances.—Tooth spacing does not exceed a 0.0005-in. tooth-to-tooth error. The involute is held to ± 0.0005 in. and the backlash to from 0.002 to 0.008 in.

This process requires hobbing of the teeth to be held to the foregoing tolerances also, as the final lapping is depended on to correct fire distortion only.

All gears are lapped the same length of time; namely, 2 min. One man operates four machines. The laps cost approximately \$8 each and are re-cut three times before scrapping. They will lap 5400 gears, which equals approximately \$0.01 per gearset.

Burnishers are used in sets of three, and cost approximately \$150 per set; a set will burnish 50,000 gears before being scrapped.

The space allotted for this paper is too limited to go into all the details pertaining to this particular subject, nor have I had the opportunity to obtain all the facts pertaining to the vast amount of energy and money expended in trying to solve it. But I hope that I have presented the picture clearly enough so that the engineers responsible for transmission design will have a little better idea as to the production man's problem in producing silent gears.

Discussion

Accuracy Assists Quietness But Is Not the Final Answer

—R. E. W. Harrison
American Society of Mechanical Engineers

WHILE one might open a discussion by remarking that "a good engineer can make almost anything work," it is doubtful if this philosophy has any place in the modern scheme of things relating to cheap and good automobiles produced on quantity-production lines. My interest in this problem is twofold inasmuch as there is an almost precisely parallel problem in most current machine-tool designs and, further, the question involves consideration of all designs calling for extremely close tolerances, no matter whether these tolerances be applied to gears, shafts or plane surfaces.

While the philosophy of incomplete knowledge is applicable to nearly all machine-shop processes, it seems that the fact that transmissions were rejected when all units had been built to master-gear tolerances indicates that the problem is one of design, rather than processing, and that accuracy, while

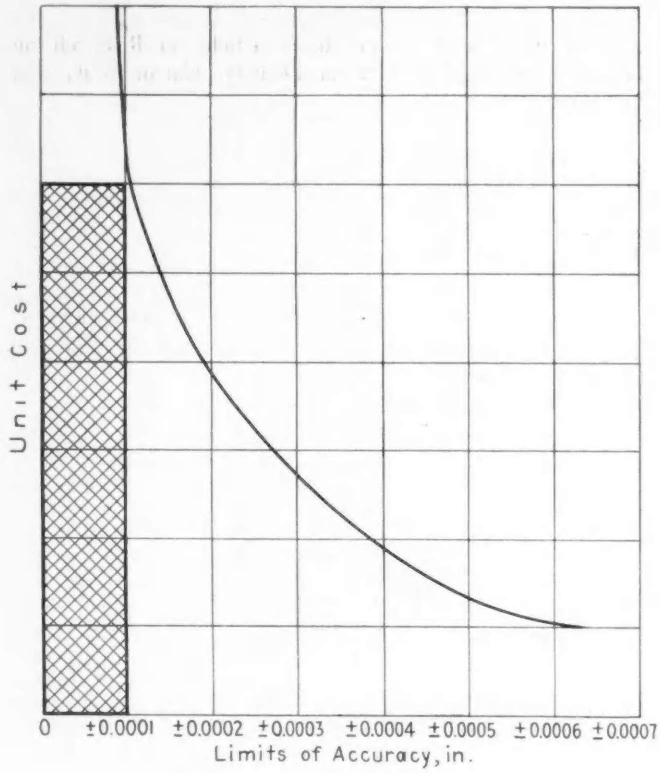

Fig. 1—Chart Showing Accuracy versus Cost
The cross-hatched portion indicates the most expensive manufacturing area

contributing to quietness, is not the final answer. If the designers feel that they must stick to gear transmissions, then is it not indicated that further research is required on such items as resonance in the assembled unit and the possibility of harmonics due to gear shapes and the natural periods of vibration characteristic of the materials used?

I have had some experience with the problems of gear grinding, and confirm that this process does not vary in its characteristics from all other grinding operations, as regards increasing cost with decreasing tolerances. The characteristic is almost invariably as per the chart shown as Fig. 1.

Commenting particularly on the gear-grinding process, we are up against two very troublesome features; (*a*) lack of grinding-wheel durability and the means for quick and accurate compensation for wear, and (*b*) the lack of stability of the wheel in resistance to bending pressures. Generally speaking, it might be said that the question of durability could be taken care of by increasing the grinding-wheel diameter; actually, however, the increased tendency of the wheel to bend under grinding stresses more than offsets the advantages gained in durability of shape.

Spur Gear Teeth Bend Under Load

The solving of an engineering problem is often accomplished by the application of the most contrary-looking practices. The increased torsional strength of a hollow shaft, as compared with a solid shaft, is typical of this. It is safe to assume that under load and impact the teeth of spur gears bend. Probably, if we designed them so that they would bend some more, the noise of impact might be reduced.

I almost hesitate to mention the possibilities of hydraulic transmission, as most hydraulic generators and motors involve an equal or greater degree of accuracy of manufacture than do gearsets; however, it is more likely that a flexible, highly efficient hydraulic transmission could be evolved by applying cheap manufacturing methods than that the same results could be obtained by the use of spur gearing, no matter how accurately it be produced. In the last analysis, the solutions of but few engineering problems are mathematically acceptable, defections from the ideal in materials, methods and men, making a compromise a commercial necessity.

Problem for Engineers

If the machine-tool manufacturer and the production superintendent cannot eliminate noise by their one weapon of accuracy, then the problem rightfully belongs in the engineering department where the solution may be found in a redrafting of materials and quantities; or, if that fails, a revision in principle.

Errors Due to Fire Changes Are Still Much Too Great

—R. S. Drummond
National Broach & Machine Co.

I AM particularly impressed with Mr. Cederleaf's comment on the method used to remove accumulative errors after hardening. Few persons in the industry appreciate the great importance of "all-over" uniformity as compared with the inspection of product for individual functional errors. The wabble or variation in helical angle is of more importance than the average of this function. The jump from tooth to tooth is more important than the accumulative index error. The relative involute curvature between the parts, as shown on one tooth, is by no means as important as the rapid variation from tooth to tooth of this function. As in cams, balls and rollers, we find a considerable permissible variation of certain errors and requirements for definite close limits on other errors.

Mr. Cederleaf gives close limits for fire changes in tooth profile. It has been my experience that variations ten times this great are still normal in many shops, due to fire changes. He has done much to reduce these variations in the gears, but there is still current in the industry the need for final correction of gear functions to remove a 0.003 to 0.005-in. error. Much of this correction may be avoided by matching irregular parts, with a final accumulation of scrap or excessive salvaging.

We call to attention the need in gear machinery for the simplest possible construction. It is very desirable that gear parts be cut with single tools rather than with multiple tools. Another feature of gear equipment is the desirability of producing the parts by using relatively unskilled operators, in substitution for the former specialist required on gear machinery. All steps in this direction require an increase in the supervision and in gear-laboratory efficiency.

A research program laid out to determine the proper location and mounting of transmissions and of gear parts will go far in securing quieter transmissions. This program would require a definite study of the acoustics, on which, as yet, little has been accomplished.

Finishing Operation Needed on Green and Hardened Gears

—**Charles R. Staub**
Michigan Tool Co.

ENGINEERING departments have never put on their drawings the tolerances necessary for quiet gears. We have seen such small tolerances put on gear drawings that they would make one's eyes water, and still we have had trouble with noisy gears. When a pair of gears is quiet, the deviation, not from the parts print, but from each other as mating parts, makes 0.0002 in. look like the width of a brick. In other words, the errors in the mating parts may be opposite, which causes them to deviate from the fundamental law of gearing; yet one might say that they are conjugate.

The ten sets of gears mentioned as ground to master-gear tolerances affords considerable proof of this statement and is the reason for the use of speeder equipment and test stands the construction and use of which are much rougher than their more polished brethren, the involute checkers, the lead checkers, the spacing checker and the like. Checking the involute, etcetera, on four spots on a gear, and finding it within the 0.0002-in. tolerance mentioned is not proof of its over-all accuracy, and to check all over would certainly be foolish when speeding checks what one wants to know anyway; namely, are the gears quiet?

The sale of checking equipment should not be prohibited, because we must maintain standards not only to give us something as a guide for interchangeability but for the sake of service parts, although perhaps that should not be mentioned. I do not know how the service on the first helical transmission could have been handled except by installing a complete new gearset. The finest job of matching we ever saw was in England. Each gear was matched with a master gear and passed. The production gears were then rematched and sent to the assembly in sets. This, no doubt, would help in maintaining a uniformity of production, but is too expensive for use in America where we do not want our expenses to be so obvious.

Facts, not opinions, are what we all want. The question is not so much what makes gears noisy as it is what to do to make them quiet. We agree with Mr. Drummond's statement that an over-all check of gears is essential to determine uniformity, but it is still more important to be equipped to finish gears so that they will check consistently uniform. We fully believe that an over-all self-generating finishing-operation such as the rack finisher on green gears, and an over-all self-generating finishing-operation on hardened gears, such as lapping, will make quieter gears than are now being made by skipping the use of one or the other operation. This procedure—that is, one in conjunction with the other—is not carried out in production by any transmission manufacturer of whom we know; but, in fact, it has been done with great success in our own plant. If this practice were followed out and the proper thought given at all times to the hardening of gear steels, we believe that grinding would not be necessary. In this connection, reference is made to an article by E. F. Davis entitled Heat Treatment of Steel Gears[1] and to his subsequent article on Hardening and Cyaniding of Steel Gears[2]; further, to Mr. Cederleaf's article on Research on Steels and Forgings for Greater Density, Machinability and Durability[3].

[1] See *The Iron Age*, July 27, 1933, p. 8.
[2] See *The Iron Age*, Aug. 3, 1933, p. 26.
[3] See *Transactions of the American Society of Mechanical Engineers*, Oct. 15, 1932, p. 127.

Rack Finishing Without Burnishing Recommended

—**A. B. Bolender**
Warner Gear Co.

I AM not surprised that Mr. Cederleaf rejected four sets of gears out of the ten sets that he had ground to limits of 0.0002 in. on curve, spacing and spiral lead. Gears with these limits are not good gears, because good gears must be within 0.0001 in. or less in variations and no grinder built today will produce gears to these limits.

Only one method, to my knowledge, will produce gears which are practically theoretically correct; that is, the rack-finishing method. Gears finished by this method should by no means be put on a burnishing machine after finishing on the rack, as this would make the gears worse, instead of better. This rack is being made to produce within a limit of a fraction of 0.0001 in. instead of a limit of 0.0002 in. as stated.

Acoustics and Mechanics Both Enter Gear Problem

—**S. M. Ransome**
Barber-Colman Co.

THE automobile industry, due to its enormous volume of product, whether mechanically or financially figured, is able to devote such an amount of time and money to research and development work as to place it in an extremely desirable position compared with that of manufacturers whose output is strictly limited in volume and at the same time very unlimited in variety. The character of Mr. Cederleaf's paper and the facts secured and presented are very convincing proof of the preceding statement. At the same time they offer a reason as to why supplying industries are often unable to match such presentation of facts and experience with studies of their own.

Bearing in mind Mr. Cederleaf's facts and figures, our opinion is that the limit of accuracy obtainable is indeed being approached. Due to the law of diminishing returns, each succeeding step becomes increasingly difficult. In other words, it is simple to remove the larger errors as measured by thousandths, but we have passed the thousandths period, are now in the "tenth" or ten-thousandths age and are approaching the "hundredth" or hundred-thousandths era, already having reached it in some instances. In our experience, we are now being handicapped for lack of extremely accurate measuring devices, although they are obtainable—at a price. As a quiet gear must be accurate in form, spacing and concentricity, it is necessary not only to have machines to produce such accuracy but inspection devices to check it.

We suggest that most of the inspection devices on the market are fundamentally defective in that they do not check

the gear in the direction of its action, but crosswise to its action. Checking gears by rotating them in contact and reading the axial errors is a check, but gears in action do not move axially. Gears operate on fixed centers as a rule and are required to do one thing; that is, to transmit power through motion in a circular path. The perfect pair of gears is that pair which has a perfectly coincident pitch-line velocity, regardless of what might happen axially. In fact, gears can be produced which run quietly; but, on the usual fixtures they check as being inaccurate, due, we believe, to the fact that the checking does not bear on this vital point of correct and harmonic pitch-line velocity.

We believe also that there are other avenues of approach. This problem is partly and indeed largely in the realm of acoustics and is as much an acoustical as it is an engineering or mechanical problem at present. We think that a transmission studied and designed to offer the greatest possible resistance to the transmission of noise would greatly lighten the gear-producer's burden.

The question of materials could be raised; that is, Why make gears of hardened steel? Makers of the earlier transmissions—of spur-gear type, using gears both as sliding clutches and power-transmission members—were forced to use this material, but this is no longer the case. In fact, we believe that such design was not the best from the standpoint of unity of function as propounded by Professor Sweet and others; that is, that each unit part should perform a given function and not two or more. However, the helical gear transmission avoids this, and having gears in constant mesh seems to me to eliminate largely the need for hardened gears.

Why not have a combination of a toughened, not hardened, gear, rough-hobbed, heat-treated, and then finish-hobbed as a final operation, this gear to run with a gear made from one of the good high-tensile-strength bronzes now obtainable? This should form an excellent wearing combination and eliminate the fire-distorting errors and grinding and lapping costs at the same time.

Many other points could be raised, but we believe further advances may be looked for rather in the line of acoustical design and change of gear materials than in further refinements in the accuracy of the finished gear-teeth, although some further advances may be made here also.

True Solution Is Grinding and Gear-Case Improvement

—**J. P. Breuer**
Barber-Colman Co.

THIS paper brings back to my mind the days when errors of 0.0005 in. in tooth form were unheard of. In fact, gears having errors in tooth form of 0.002 in. were considered first class and hobbed gears having spacing errors of 0.00075 in. from tooth to tooth and errors between non-adjacent teeth of 0.003 in. were considered as being within the regular commercial tolerances. Yet noisy gears are still with us and always will be.

Improvements are being made by the machine-tool maker, the hob and the gear-shaper-cutter maker, and by all others who are in this business. But the demand for still quieter gears is being and no doubt will continue to be made not only for automobiles but for every machine on which gears are used. This is as it should be. But the problem of keeping in step with the demand for quieter gears costs too much if present-day grinding-methods are used. In my opinion, grinding will be the real solution, along with improvements in the gear cases. We hope that gear noises, especially those in transmission cases, may be deadened by soundproof cases and that gears, such as are being produced by hobbing and shaping, will fill the bill.

Acoustic Science Assists In Seeking Quiet Gearing

—**Joseph Geschelin**
Engineering Editor, Automotive Industries

IN seeking quiet gearing, both production men and engineers must turn to the fundamental science of acoustics for assistance. Given the best product of the gear department and the best design that the engineer can develop, it is still possible to run into serious rejections when the car is finally put through its paces with all its units in place.

The reason for this anomaly is that certain frequencies of sound below the audible range of the human ear—and these may be found in a truly silent transmission—may become important and certainly audible when mounted in the chassis. This may be caused by the sound-box effect of the body or location in the chassis and/or type of mounting. The reinforcement of the inaudible frequency is quite analagous to the effect gained by mounting a tuning fork on the proper-sized sound-box. The perplexing thing about it is that the transmission may be really quiet in one chassis and a howler in another chassis either of a different make or with a different style of body. This makes it tough on the supplier who builds for the industry.

Research Methods Suggested

The answer lies in the development of a research project designed to measure the various significant frequencies in a transmission not considered as an individual unit but when mounted in the car. When the troublesome sound is located it must be taken out, even if it be in the inaudible range. This method of attack has been investigated by the General Motors Corp. Research Laboratories during the last two years.

One way to handle the problem of unit inspection is to develop some inspection device which would seek out the frequencies known to be important in a given chassis design. This is easier said than done, but is not impossible of accomplishment.

Some suggestions have been made concerning the possibilities of insulating a transmission case to achieve quietness. This view is untenable, since the problem is not one of keeping the sound from coming out of the gearbox as much as it is a matter of eliminating certain sounds from the gearbox. Moreover, it is well known that it would take a very heavy layer of any good insulating medium to keep sounds from coming out. However, the simplest method is to get insulation through the design of the mounting. At this point it is possible to work out a construction which would prevent vibration from being transmitted to the chassis and at the same time prevent chassis vibrations from entering the transmission.

Improvement in Gear Steels and Drop Forgings Needed

—S. O. White
Warner Gear Co.

WE are already making transmissions which are commercially satisfactory when chassis and mounting conditions are right, but what we need is to have all of our transmissions as good as the best ones that we are already producing. To bring this about, a great deal of work remains to be done by the steel makers and the drop forgers. Steel making and forging have not made anything like the progress in recent years that has been made by the manufacturers of such things as machine tools, gear-cutting equipment and gear cutters.

Mr. Cederleaf has given us his experience with gear-tooth grinding; but, in large-quantity production, we have not found that the results justify the cost. Gear-tooth grinders are subject to about the same general mechanical variations as are the various types of gear-tooth-cutting equipment, and, in a quantity-production run, there will be a similar variation in the quality of the output.

The cost of producing quiet transmissions is a vital factor and, after the transmission reaches a certain point of excellence, additional refinements cost more than they are worth, especially in view of the fact that the desired results can be obtained more cheaply outside of the gearbox.

Mr. Geschelin's comments as to the parts which the chassis design and the mounting play in transmission noise agree exactly with our experience. As we, throughout the years, have made transmissions for a great variety of cars having every kind of chassis design and type of engine, it has long been our observation that, of two identical transmissions, both satisfactory when passed over our sound-testing equipment, one of them will be satisfactory when mounted in the car and the other will not. We have also had the experience that transmissions which would not pass our sound test would be perfectly satisfactory when mounted in certain cars, with no gears in it whatever but having simply a straight shaft mounted in a standard production gearbox, giving the drive from the engine clutch to the rear axle, will have objectionable periods, vibrations and noises.

Mr. Geschelin commented also as to sound insulation or absorbing devices and materials directly in the transmission itself. Our experience has likewise been that anything of this character which is a noticeable help gets to be so bulky, or so expensive, or entails such other mechanical difficulties, that it does not constitute a practical solution. As already mentioned, more can be done in the chassis and in the mounting, directly along this line, for very much less money than in the transmission itself.

One of the more important external aids that has been developed is the spring damper within the engine clutch. Another aid that accomplishes a great deal is the soundproofing of floorboards and toeboards. In spite of floorboard insulation, however, more or less noise is transmitted up through the hand levers. Putting the parking-brake hand-lever over onto the frame has been a help, and some form of remote control in which the control lever and its mounting pedestal do not come up through the floor and are not directly connected to the cover of the transmission constitutes a further help.

Better to Get Quietness by Master-Gear Accuracy

—H. D. Tanner
Pratt & Whitney Co.

MR. CEDERLEAF'S report of the test of ten sets of helical gears ground to master-gear tolerances is very significant in that, while only six sets were satisfactory, the test was considered a proof that master-gear accuracy is at least desirable. Evidently, the rejection of four transmissions was not considered to be due entirely to the gears themselves. It might also be suspected that the standard of quietness used in this test was higher than that used for production transmissions, but not higher than the standard which will have to be used eventually.

Other things being equal, gears ground to the tolerances stated should have resulted in ten satisfactory transmissions. Let me say here that master-gear gear-tolerances are now ± 0.0001 in. The machine which uses the master gear is capable of reproducing that accuracy, but it is not expected to do so in production because enough time cannot be taken. If time enough is taken to produce an accuracy of ± 0.0002 in. and the gears are lapped to polish the tooth surface, we believe everything necessary has been done to the gear teeth to satisfy any reasonable requirement. The design and workmanship of the rest of the transmission must be such that full advantage is taken of this accuracy. Gear accuracy, while of the first importance, will not of itself produce a silent transmission.

Mr. Cederleaf asks the transmission engineers to find a way to produce a better transmission when using gears which are not very close to master-gear accuracy. I would rather ask them to find a way to take full advantage of gears which are very close to master-gear accuracy as being more apt to bring success. The average transmission is a very able amplifying device, and if we knew why we probably could remove the cause. After we had done that we would not find the use of accurate gears as disappointing as even the maker of the gear-finishing machine does now.

The paper states that master gears sell for $50. The average price is $35, but if as many master gears were made per hour as the transmission builder makes ordinary gears, the master gears would sell for much less than they do. Master gears are ground on production machines by a 65 cents per hr. man.

Beginning in about 1920, when it seems to have suddenly occurred to many of us that transmissions were not very quiet, fortunes have been spent in an attempt to make spur-gear transmissions quiet without increasing the cost of the transmission. Even by increasing the cost slightly it was not done, although some of us tried to change the definition of the word "quiet."

In the last few years it has been found that a dollar or two added to costs allowed the use of helical gears, and a standard of quietness that was a long step nearer to silence. It must have been known years ago that the helical gear would do what it has, but that dollar or two stood in the way so long that the greater cost in the long run was the continued use of the spur gear. Since quieter gears are now demanded, it is to be hoped that the dollar will not stand in the way too long.

The machine-tool builder is ready to lower the cost of ground gears to less than the figure given and to produce

gears having still smaller errors. However, it does not seem reasonable to expect that gears ground to nearly master-gear accuracy can be made for the cost of lapped gears. I have not yet seen any statement that the helical gear can be made for the cost of the spur gear.

Mr. Cederleaf concludes that the ground gear would be the answer to his question if it were not for its higher cost. Using his method of calculation, which results in a total factory cost of $1.43 per set of four ground gears, I can see a reduction to approximately 90 cents possible by improvements in gear-grinding methods. The cost of the ground gear would then amount to approximately 0.7 cent per tooth more than that of the lapped gear.

To the plea that the transmission engineer and the machine-tool builder give the production engineer more help, I would ask a question of the man who is going to buy this automobile. It is: "If the silent transmission is demanded and not merely desired, is it not worth 0.7 cent per tooth more?"

Fortify Present Accuracy To Make Gears More Quiet

—Perry L. Tenney
Olds Motor Works

AFTER presenting the production side of the story, Mr. Cederleaf has bluntly put the problem up to the engineer for solution, but in this instance he is partly justified. All real progress in the development of transmissions has come about through the coordinated efforts of the engineering and production groups and, likewise, all further progress must be made by the coordinated efforts of both groups. A building, no matter how well built, will immediately or rapidly sag out of shape or go to pieces and fail in its purpose unless set on a proper foundation. Likewise, accurate gears will be noisy and immediately go to pieces and fail in their purpose unless they are run on a proper foundation.

In obtaining the answer to the question in the title of the paper, I would say that the production and the machine-tool-builder's parts are to fortify better the accuracy already achieved. We do make accurate gears as outlined in the paper, but this accuracy is by no means "nailed to the mast," for Mr. Cederleaf well knows that, no matter how well things are running in the shop, it is difficult to maintain the accuracy he specifies. Any slight deviation, which usually occurs the minute one's back is turned, can upset all these standards.

With this high average established, there can be little betterment in transmissions until we accomplish better design which will permit the gears to be operated under more favorable conditions. In this I refer to rigidity of mounting, as affected by deflection of mountings and shafts and by misalignments resultant from the required bearing clearances and, to a lesser degree, to the features of resonances and periodic vibrations in all of the associate members of the construction. I believe there is much to be done along these lines before any improvement in gear accuracy will be acquired. However, with the raising and maintaining of an average closer to the good side of our present range, most of the desired improvement in performance can be realized from better engineering of the associate members or of the aforementioned foundation.

Referring to the figures on the relative merits of grinding and lapping, I believe this can be answered entirely from the engineering-design standpoint. We can all recall instances where the desired gear accuracy of a well-designed symmetrical gear-blank can be obtained by lapping. However, the same gear, when designed with unsymmetrical hubs and webs, will have an amount of volumetric change in the heat treatment which is beyond the range of the lapping process; therefore, the more expensive grinding process must be used.

To illustrate this point further, I believe it is safe to say that we can ignore warpage or fire distortion under present-day standards, that is, when steel, structure, forging methods and proper design of a gear blank are taken into consideration. Warpage and distortion can take place only when one or more of these elements are ignored. There is, however, a definite volumetric change of the steel in the heat treatment. This volumetric change is constant to exactly the same degree as this process from mill to final treatment is constant. Improper design, giving unsymmetrical disposition of mass in a gear blank, will adversely affect the volumetric change of the gear and, inversely, proper design will hold this change to within limits and within the requirements of the lapping process. Grinding is justified only when the economies of an unsymmetrical design will offset the additional cost.

In the foregoing I refer only to high-quantity production; for it is obvious that grinding is the only method of obtaining accuracy on small quantities where the cost of determining necessary data for fire-change allowances and the like, incident to the lapping process, makes this prohibitive.

Gearbox-Resonance Research and Better Mounting Needed

—John G. Wood
Chevrolet Motor Co.

SEVERAL years ago I had occasion to observe the results of the developments in the manufacture of transmissions and transmission gears by the various processes described in Mr. Cederleaf's paper. The most significant thing was the fact that when all the development work covering the new processes was completed the rejections on finished transmissions dropped from 35 to 0.5 per cent. This result could be attributed only to the care and precision that were exercised in obtaining uniform control throughout every stage in processing, from raw material to the finished unit.

In spite of the uniformity which was finally obtained by these methods, it was still evident that the transmission units produced failed to be satisfactory if judged from a standpoint of absolute quietness. From a commercial viewpoint it is therefore apparent that, if absolute quietness is to be demanded in gear-driven transmissions, it is up to the designers to provide ways and means of obtaining such quietness in some other manner than can now be obtained with conventional designs under the very best practice in manufacture. It is probable that the best results in this direction may be obtained by a more careful study of transmission mountings, and also with a more thorough study of the elimination of resonance in the transmission case.

It is unlikely that any decided improvement can be expected in gear design, so that the logical lines along which the designer can best apply his effort will be in the insulation of such noise as still remains under the most uniform conditions of production.

Effect of Gasoline Volatility on Engine Economy

By Neil MacCoull
Director of Mechanical Research, The Texas Co.

REPETITION of the 1923 and 1924 Cooperative Fuel Research Steering Committee's motor-car tests, using modern cars and gasolines ranging in end points from 312 to 432 deg. fahr., provided the data on which this paper is based.

Supplementary runs were made also on a variable-compression engine to learn the optimum performances of these gasolines if an engine were designed around them. The experimental work covered is divided into three groups.

Experiments conducted under Group 3 are particularly interesting because the single-cylinder C.F.R. engine used made operation possible with optimum compression ratios and mixture temperatures, which result in maximum thermal and volumetric efficiencies, respectively. This group comprised four major steps, and data for each one are presented.

Design of engines must follow the gasoline which the oil companies find they can market most economically, Mr. MacCoull thinks.

MEMBERS of the Society were much perturbed, some ten or twelve years ago, about what seemed to be an inevitable increase in the end point of gasoline. A study was made, therefore, of the effect of gasoline end points on the fuel economy, or miles per gallon, on various automobiles on the road. The ultimate object was to determine the volatility of gasoline which would result in the greatest mileage per barrel of crude run to the refineries. Records of these very extensive experiments which were made on more than 50 cars, and during which about 111,000 miles were covered on the road, are described in the S.A.E. TRANSACTIONS[1] for 1923 and 1924. The gasolines used varied in volatility, as indicated by their end points, from 403 to 472 deg. fahr. Incidentally, these tests to determine what constituted the best gasoline as regards volatility, considered on a broad economic basis, formed the first project undertaken by the Cooperative Fuel Research Steering Committee, whose recent work has resulted in the C.F.R. engine and in test procedure for measuring the antiknock value of gasoline.

During the last decade the automotive and oil industries have seen revolutionary changes. Gasoline end points have dropped instead of rising as was feared; gasoline antiknock properties[2] have been "discovered," measured and increased; and engine compression ratios have climbed in order to take advantage of the high antiknock values now available.

Because of these facts, the company with which I am associated considered it desirable to repeat the C. F. R. tests on modern cars with gasolines ranging in end points from 312 to 432 deg fahr. To complete the picture, runs were made on a variable-compression engine to learn the optimum performances of these gasolines if an engine were designed around them. The experimental work covered in this paper is divided into three groups, as follows:

Group 1.—Tests were run on 14 cars on a chassis dynamometer with the carburetor adjustments as found. Fuel-consumption runs were made under level-road conditions at 20 and 40 m.p.h. and runs were added to show the maximum power available as well as the acceleration rate with each of five gasolines having different volatility.

This group shows what might be expected in the average car as it is used today if a change were made in the volatility of the upper end of the gasoline-distillation curve.

Group 2.—Tests were made on the effect of adjusting the carburetors for each gasoline. These tests were run on a

[This paper was presented at the International Automotive Engineering Congress, Chicago, Aug. 30, 1933.]

[1] See S.A.E. TRANSACTIONS, vol. 18, part 1, p. 16; see also vol. 19, part 2, p. 1.

[2] U. S. patents, No. 1,239,099 and No. 1,239,100 reveal that knocking was recognized as a fuel characteristic at least as far back as 1915, although it was not generally recognized by the petroleum industry until several years later.

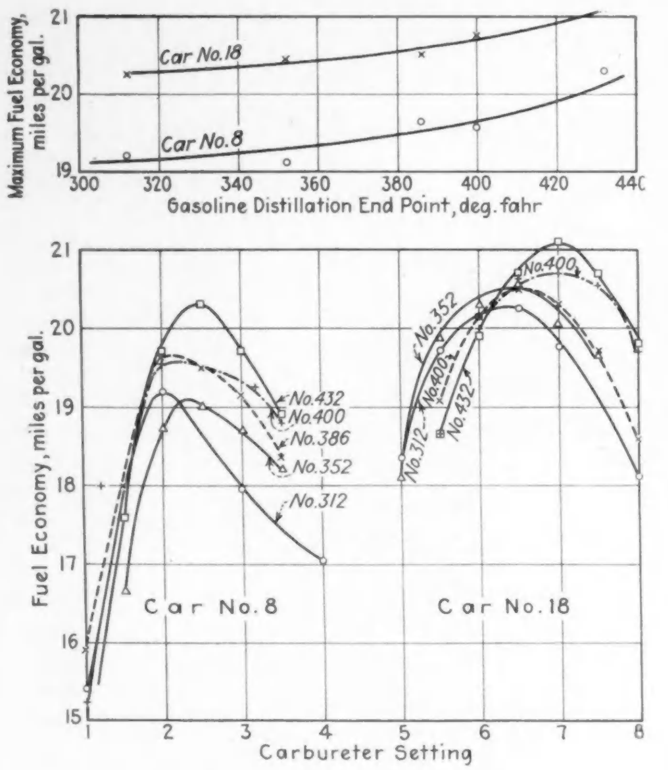

Fig. 1—Fuel Economy Versus End Point
The cars were operated at 40 m.p.h. under level-road conditions.

chassis dynamometer on two cars only, since most cars are provided with carburetors which do not allow wide ranges of carburetor adjustments to be made easily and quickly.

This group shows what could be expected in average cars on the road today if a change were made in the "upper-end" volatility, and *if* each carburetor were adjusted for the new gasoline.

Group 3.—Tests were run on a single-cylinder engine with adjustments of the compression ratio, mixture temperature and mixture ratio made for each gasoline. The mixture temperatures were the lowest which could be expected to give dry mixtures and good distribution in multi-cylinder engines, and the compression ratios were the highest which could be used without detonation. The mixture temperatures were thus adjusted to take the best advantage of the changes in volatility and "dew point," and the compression ratios were adjusted to take advantage of the change in antiknock value of the gasolines which usually accompany a change in their upper-end volatility.

This group shows what could be expected in future cars if designed to use gasolines of different upper-end volatility.

Fuels Used

Five gasolines were used in these experiments. One was a commercial motor gasoline, and four others were made up as follows: Two of high volatility (No. 312 and No. 352) were made by steam stilling the motor gasoline. Two of low volatility were made up also, one (No. 400) by blending the original motor gasoline with some of the heavy ends from the steam still, and the other (No. 432) by blending the motor gasoline with a light fraction from kerosene. Thus, four of the five gasolines were made entirely from the same source, which was particularly significant in regard to the range of antiknock values secured. Detailed test data on these five gasolines are given in Table 1.

In this paper, gasoline end point is referred to as a measure of volatility. This follows general practice, although it is realized that the 90 per cent point is a much truer criterion[3]. Since the various gasolines used in the experimental work reported here had distillation curves of somewhat similar shape, there is a consistent relation between end points and 90 per cent points which excuses the liberty of referring to volatility in terms of end points.

No adjustments were made on any of the 14 cars. They were tested with the adjustments used on the road. All runs were made at an air temperature of 70 deg. fahr. The individual data are given in Tables 2 to 4, from which the following summary was made.

Average Car Performances

Code No. of Gasoline Used[a]	312	352	386	400	432
90 Per Cent Point, deg. fahr. (Corrected for Loss)	252	306	332	352	395
A—Miles per Gallon:					
Level Road:					
20 m.p.h.	17.0	17.8	17.92	18.6	18.5
40 m.p.h.	15.3	15.8	16.10	16.5	16.5
Wide-Open Throttle:					
20 m.p.h.	6.5	6.6	6.7	6.9	6.9
40 m.p.h.	7.2	7.4	7.4	7.5	7.5
B—Acceleration: from 10 m.p.h.					
Speed after 14 sec.	33.7	33.8	34.0	33.7	33.6
Speed after 16 sec.	36.7	36.7	37.2	37.0	36.6
C—Rear-Wheel Traction:					
Wide-Open Throttle; lb.					
20 m.p.h.	430	438	438	437	430
40 m.p.h.	405	407	407	405	395

[a] The code numbers correspond to the end points

From these figures it can be seen that very little change in miles per gallon results from a change in gasoline volatility over the range tested. The change is undoubtedly too small to be observed by any motorist, for we doubt if car owners would be able to detect differences of less than 10 per cent between different gasolines. Taking the very small differences into consideration, we found that:

(1) The mileage either on level roads or when climbing maximum grades appears to be a maximum for a gasoline which would lie between No. 400 and No. 432, the two heaviest tested.

Increasing the volatility caused a steady decrease in mileage. The total range was about 7 per cent, the best averaging about 3 per cent better than the original motor gasoline used as a reference and the worst being about 4 per cent less.

This range in results is almost equal to the range in specific gravities of the fuels used; so that, if the results had been

[3] See S.A.E. TRANSACTIONS vol. 23, 1928, p. 42 and p. 368; see also vol. 24, 1929, p. 240.

Table 1—Detailed Test Data on the Five Gasolines Used

Gasoline Code No.	312	352	386	400	432
Gravity:					
A.P.I.	69.8	64.0	61.8	56.4	57.8
Specific	0.703	0.724	0.732	0.753	0.748
Sulphur, per cent	0.021	0.035	0.060	0.084	0.048
Viscosity—Absolute 60 deg. Fahr.	0.458	0.522	0.559	0.662	0.684
Doctor Test	Neg.	Neg.	Neg.	Neg.	Pos.
Gum:					
Copper Dish	3	0	0	4	0
Bureau of Mines	0	0	0	0	0
Accelerated	0	7	0	0	0
Corrosion:					
Copper Dish	Good	Good	Good	Bad	Bad
Copper Strip	No	No	No	No	No
Iodine Value	66	61	60	57	47
Aniline Point	49.2	46.9	46.1	44.4	48.1
Reid Vapor Pressure	9.7	9.1	7.1	6.9	6.2
Distillation:					
Initial Boiling Point	80	92	85	100	100
10	112	127	126	148	140
20	130	150	154	186	174
30	146	173	180	224	208
40	164	197	208	251	242
50	182	221	234	276	277
60	198	240	256	295	311
70	214	260	280	318	338
80	230	283	310	334	378
90	256	312	342	358	404
95	282	335	370	378	420
End Point	312	352	386	400	432
Per Cent Recovered	98.0	98.0	97.5	98.0	98.0
Octane No.					
C.F.R. Research Method	74	70	69	65	58
C.F.R. Motor Method	72	69	67	65	58
Hydrocarbon Analysis, per cent:					
Unsaturates	17.6	14.0	13.6	13.8	10.7
Aromatics	5.0	7.4	10.4	11.1	9.3
Naphthenes	23.0	21.0	19.3	17.3	15.3
Paraffines	54.4	57.6	56.7	57.8	64.7

expressed in miles per *pound* of fuel, even these small differences would have almost disappeared.

(2) The acceleration with the commercial gasoline was better than with gasolines of either greater or lesser volatility.

(3) The power available was not exceeded by any gasoline of higher or lower volatility than the reference gasoline. The gasoline of next higher volatility was equal to it, but still greater volatility resulted in a loss.

Group-2 Data.—In this group, two cars were tested with a wide range of carburetor settings. Difficulty in making such carburetor adjustments limited these tests to cars Nos. 8 and 18, which were provided with a needle-valve carburetor-adjustment.

The curves in Fig. 1 show the results. For each fuel there was a carburetor setting which gave a definite maximum fuel economy, but this maximum was developed at different carburetor settings for each fuel. Carburetor settings can thus give apparently contradictory evidence in regard to mileage from gasolines of various volatility. For example, consider the curves for car No. 18 at the lower right in Fig. 1.

(1) In the runs made at the carburetor setting indicated as 1½ (that is, 1½ turns of the needle valve from the closed position) the mileage secured and the relative order of merit are as follows:

Gasoline No.	Fuel, Miles Per Gal.
352	19.9
312	19.7
386	19.1
400	18.7
432	18.7

In other words, the *lower* the volatility the lower the fuel economy.

(2) At a carburetor setting of 2.3, there is no noticeable difference between the various gasolines, and:

(3) At a carburetor setting of 3, the mileage and relative order of merit are as follows:

Gasoline No.	Fuel, Miles Per Gal.
432	21.1
400	20.7
386	20.3
352	20.2
312	19.8

In other words, the lower the volatility the ***higher*** the economy. These results are the reverse of those shown in (1).

One more comparison of these data was made on the basis of the peak or maximum mileages secured. The carburetor was thus given the ideal setting for each fuel. The results given at the top of Fig. 1 indicate that the best mileage can be obtained with the least volatile gasoline, although the total difference in economy resulting from changing the end point 120 deg. fahr. was hardly 5 per cent. This agrees with the Group-1 results.

Group-2 Conclusions.—The relative mileage secured from gasolines of different volatility depends on the carburetor setting. For average settings, as shown from Group 1, or optimum settings from Group 2, the more volatile the gasoline, the less the mileage per gallon; but the change is too small to be of importance.

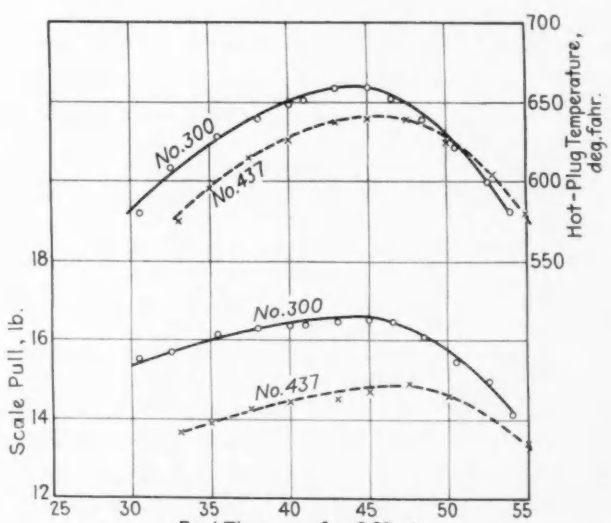

Fig. 2—Effect of Mixture Ratio on Power Output and Hot-Plug Temperature

Table 2A—Fuel Consumption—Level-Road Conditions—Miles Per Gallon

Gasoline Code No.		312	352	386	400	432	312	352	386	400	432
		20 M.P.H.					40 M.P.H.				
Car No.	21	16.92	17.15	17.10	18.82	19.10	15.50	16.00	16.41	16.88	17.10
	22	19.97	17.82	18.00	18.50	17.74	15.19	15.94	15.94	16.13	16.25
	23	15.70	16.30	17.22	17.97	19.00	14.90	15.27	15.82	16.25	15.99
	17	18.40	20.75	20.95	21.20	20.27	16.63	17.50	18.13	18.57	18.80
	18	23.70	23.60	22.90	22.63	21.20	18.95	18.90	19.63	19.23	18.55
	20	10.80	11.10	10.00	12.40	11.30	10.20	10.40	10.00	12.30	10.80
	1	11.78	12.84	13.25	13.95	13.65	12.76	13.92	14.08	14.60	14.76
	14	17.66	18.40	18.57	19.80	19.85	15.10	15.78	16.01	16.60	16.80
	8	14.30	14.95	15.15	15.35	16.88	14.10	14.65	14.25	14.63	14.60
	15	12.87	18.94	18.81	19.53	19.57	15.98	16.69	16.55	17.26	17.15
	7	11.50	11.50	12.10	12.20	12.70	11.97	12.16	12.27	12.40	12.50
	13	20.18	21.00	21.47	21.50	21.33	16.80	17.87	17.95	17.95	18.54
	2	25.66	26.60	26.63	27.40	28.06	20.80	21.60	21.85	22.13	21.90
	16	18.12	18.50	18.76	19.30	18.40	15.44	15.60	16.26	16.23	16.43
	Average	16.97	17.82	17.92	18.64	18.50	15.30	15.80	16.05	16.51	16.45

Group-3 Data.—Experiments conducted under this group are particularly interesting because the single-cylinder C. F. R. engine[4] used made operation possible with optimum compression ratios and mixture temperatures which result in maximum thermal and volumetric efficiencies, respectively. In each run the carburetor was set for optimum power by means of a U. S. Army type[5] "hot plug." This was found to be more convenient than by use of the beam scale, and, as can be seen from Fig. 2, both methods of setting the carburetor give approximately the same result. This group of experiments was made up of the following four steps:

(1) Fixed mixture-temperature and fixed compression-ratio.

(2) Fixed mixture-temperature and optimum compression-ratio.

(3) Fixed compression and optimum mixture-temperature.

(4) Optimum compression and optimum mixture-temperature.

Step No. 1

The first step consisted of testing each gasoline at the same compression ratio (low enough to give no detonation from the worst fuel) and the same manifold temperature (high enough for dry mixtures with the heaviest fuel). The results are tabulated below:

Effect of Volatility on Power Economy, with Fixed Compression and Temperature

Gasoline No.	Horsepower	Fuel Consumption: Pt. per Hp-hr.	Fuel Consumption: Lb. per Hp-hr.	Hot-Plug Temperature, Deg. Fahr.
312	2.86	0.960	0.703	652
352	2.86	0.956	0.720	652
386	2.86	0.963	0.735	653
400	2.86	0.963	0.753	653
432	2.86	0.963	0.750	655

This tabulation shows that fuel volatility has practically no effect on power or fuel consumption at wide-open throttle *when measured by volume:*

(1) If the compression ratio and mixture temperature are fixed.

(2) If the carburetor is reset to give best power. Resetting is necessary because the viscosities and specific gravities of the gasolines change with their volatility, No. 432 having almost 50 per cent higher viscosity than No. 312.

The foregoing test conditions were: r.p.m., 900; compression ratio, 4.0:1; air temperature to carburetor, 100 deg. fahr.; mixture temperature, 201 deg. fahr.; jacket temperature, 210 deg. fahr.; spark advance, 29 deg.

Step No. 2

Advantage was taken of the increased antiknock value which usually accompanies increases of volatility (from a given source), *by increasing the compression ratio* to the point of incipient detonation for each fuel.

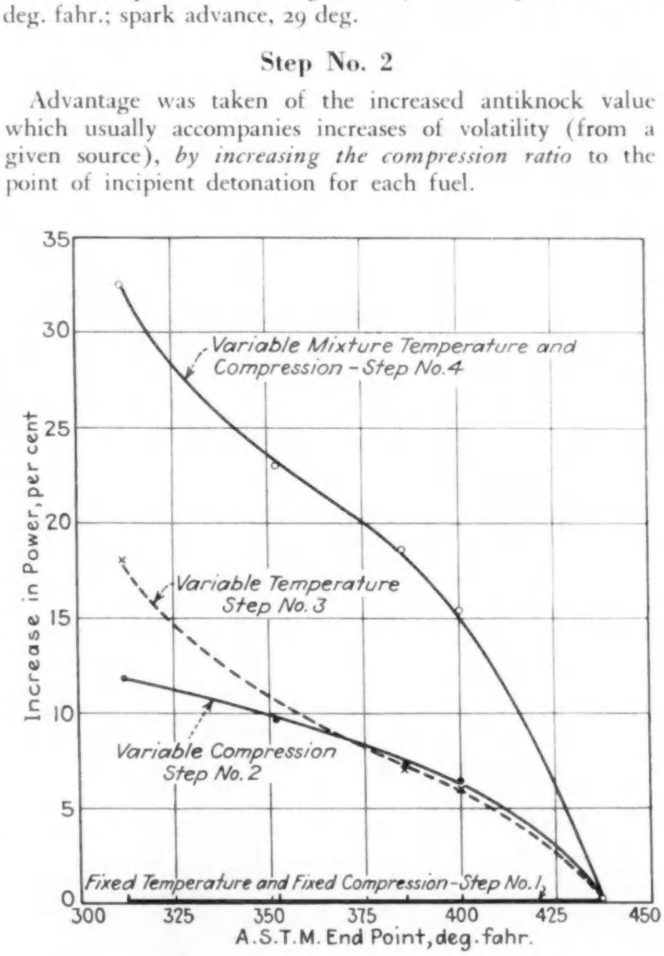

Fig. 3—Effect of Volatility on Power Output under Various Conditions of Engine Operation

[4] The shrouded valve and other equipment of the Motor Method were used throughout; see A.S.T.M. tentative standard D-357-33T.

[5] See U. S. Army Specification No. Y-3557-F, for aviation gasoline.

EFFECT OF VOLATILITY AND HIGHEST USEFUL COMPRESSION RATIO (H. U. C. R.)

Gasoline No.	Antiknock Value (C.F.R.M.)	Compression Ratio	Power	Increase Per Cent	Fuel Consumption: Pt. per Hr.	Fuel Consumption: Pt. per Hp-hr.	Fuel Consumption: Lb. per Hr.	Fuel Consumption: Lb. per Hp-hr.	Hot-Plug Temperature, Deg. Fahr.
312	72	4.72	3.15	11.8	3.12	0.99	2.20	0.726	684
352	69	4.63	3.09	9.8	2.98	0.97	2.16	0.732	682
386	67	4.42	3.03	7.2	2.90	0.96	2.12	0.732	678
400	65	4.37	3.02	7.0	2.87	0.95	2.17	0.747	671
432	58	4.00	2.82	0.0	2.78	0.99	2.09	0.773	666

The foregoing test conditions were: r.p.m., 900; compression ratio, incipient knock; carburetor-air temperature, 100 deg. fahr.; mixture temperature, 201 deg. fahr.; jacket temperature, 210 deg. fahr.; spark, standard automatic, 29 deg. at 4:1 compression ratio.

Several interesting points, brought out here primarily because the increased antiknock value permitted an increase of nearly three-quarters of a compression ratio, are:

(1) Power increased about 12 per cent with the most volatile fuel. See Fig. 3.

(2) Fuel consumption, by weight, which is of special interest in aviation, decreased 6 per cent with the most volatile fuel.

Step No. 2-A

This was supplementary to Step No. 2, but was run throughout with gasoline No. 312 for the purpose of showing *the effect of compression ratio only*. The previous step, No. 2, showed the combined effect of gasoline and compression ratio.

EFFECT OF COMPRESSION RATIO ONLY

Compression Ratio	Horse-power	Power Increase Per Cent	Fuel Consumption: Pt. per Hr.	Fuel Consumption: Pt. per Hp-hr.	Hot-Plug Temperature Deg. Fahr.
4.0	2.11	0.0	2.41	1.14	630
4.2	2.17	3.0	2.41	1.11	640
4.4	2.25	6.5	2.41	1.07	647
4.6	2.32	10.0	2.41	1.03	658
4.8	2.41	14.0	2.41	1.00	664
4.95	2.46	16.5	2.41	0.98	665

The foregoing test conditions were: r.p.m., 900; carburetor-air temperature, 73 deg. fahr.; mixture temperature, 200 deg.

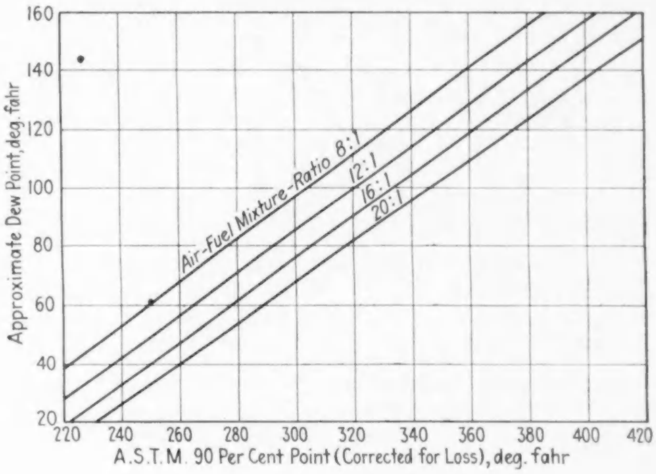

Fig. 4—Gasoline Dew Points at Atmospheric Pressure

fahr.; jacket temperature, 212 deg. fahr.; spark advance, standard automatic; carburetor reset for maximum hot-plug temperature at each compression ratio.

Notice that the result of increased compression ratio (when using a given fuel) was an increase of power output, and thus of efficiency, since the fuel consumption (measured by "flow rate") was unaffected. This is an interesting difference from Step No. 2, where various fuels were tested at their best compression ratios; for, in the latter case, the fuel-consumption rate did vary from one gasoline to another. This test, Step No. 2-A, thus indicated that the increased consumption rates with increased volatility in Step No. 2 were not due to increased compression ratio, and must therefore have been caused by the characteristics of the fuels themselves.

Step No. 3

In Step No. 3 advantage was taken of the volatility of the various gasolines, *by heating the mixture* from the carburetor only enough to be sure that is was dry. A single-cylinder engine does not require a dry mixture, but all multi-cylinder engines need dry mixtures for good distribution. A dry mixture is primarily an intake-manifold requirement.

The temperatures to which the gasoline mixtures were heated were 50 deg. fahr. above the dew points read from the curves in Fig. 4. This chart (prepared from O. C. Bridgeman's

Table 2B—Fuel Consumption—Full-Load Conditions—Miles Per Gallon

Gasoline Code No.	20 M.P.H.: 312	352	386	400	432	40 M.P.H.: 312	352	386	400	432
Car No. 21	5.86	5.95	6.05	6.27	6.22	5.90	6.16	6.20	6.50	6.40
22	5.80	6.06	6.16	6.20	6.14	6.16	6.56	6.58	6.63	6.60
23	6.10	6.32	6.30	6.42	6.44	6.27	6.60	6.40	6.80	6.64
17	6.16	6.47	6.90	7.08	7.13	7.92	8.12	8.34	8.40	8.52
1	5.40	5.40	5.40	5.50	5.55	6.10	6.20	6.20	6.45	6.20
14	5.84	5.90	5.94	6.05	6.34	6.30	6.50	6.50	6.53	6.58
15	7.6	7.8	7.9	7.9	7.9	8.15	8.32	8.30	8.15	8.45
7	5.12	5.62	5.58	5.74	5.62	6.40	6.40	6.56	6.24	6.20
13	6.24	5.84	6.38	6.42	6.62	6.70	6.80	7.00	7.12	7.04
2	9.90	10.20	10.06	10.20	10.28	11.60	11.76	11.60	11.80	11.96
16	6.84	7.28	7.30	7.68	7.66	7.64	7.84	7.96	8.20	7.96
Average	6.45	6.62	6.72	6.86	6.90	7.19	7.38	7.42	7.52	7.50

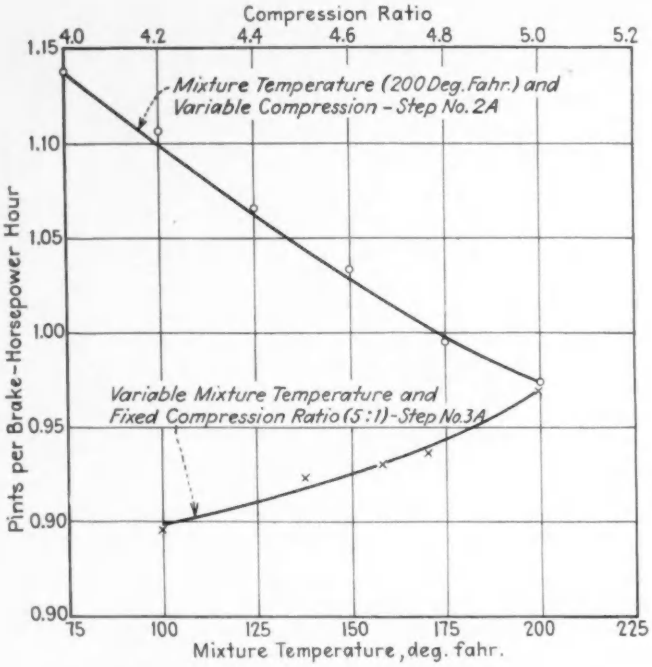

Fig. 5—Fuel Consumption with No. 300 Gasoline on the C.F.R. Engine at 900 R.P.M.

early C. F. R. work) is a very handy approximation for obtaining dew points from the 90 per cent A. S. T. M. point for distillation loss. The values so obtained will be within 3 or 4 deg. fahr. of the true values for commercial gasolines. Greater accuracy, where desired, will require consideration of a correction for the slope of the distillation curve at the 90 per cent point[6]. The additional 50 deg. fahr. was arbitrarily added to these values because the mixture passes through the manifold of any engine so fast that equilibrium cannot be established in the time available.

Effect of Volatility on Manifold Temperatures for Dry Mixtures

Gasoline No.	A.S.T.M. 90 Per Cent Point (Corrected) Deg. Fahr.	Dew Point, Deg. Fahr.	Manifold Temperature, Deg. Fahr.	Horsepower: Actual	Horsepower: Increase, Per Cent	Fuel Consumption: Pt. per Hr.	Fuel Consumption: Pt. per Hp-hr.	Hot-Plug Temperature, Deg. Fahr.
312	252	51	101	3.23	18.0	3.26	1.01	680
352	306	89	139	3.03	10.8	2.98	0.98	667
386	332	108	158	2.94	7.1	2.87	0.98	666
400	352	122	172	2.90	6.0	2.86	0.99	659
432	395	153	203	2.74	0.0	2.67	0.99	682

The foregoing test conditions were: r.p.m., 900; compression ratio, 4:1; carburetor-air temperature, 100 deg. fahr.; jacket temperature, 210 deg. fahr.; spark advance, 29 deg.

The most interesting feature here is the 18 per cent gain in power resulting from lowering the mixture temperature over a range of 100 deg. fahr., as is permissible for equivalent "dryness" with each gasoline. The power gain was due primarily to the denser charge supplied to the cylinder and, of course, the amount of fuel burned increased at about the same rate, so that the fuel consumption per horsepower remained substantially constant if measured by volume.

[6] See S.A.E. Transactions, vol. 24, 1929, p. 242.

Step No. 3-A

This was supplementary to Step No. 3, and was run on No. 312 gasoline throughout, *to show the effect of temperature only*. The previous step, No. 3, gave the combined effect of temperature and gasoline.

Effect of Mixture Temperature Only

Mixture Temperature, Deg. Fahr.	Horsepower	Increased Power, Per Cent	Fuel Consumption: Pt. per Hr.	Fuel Consumption: Pt. per Hp-hr.	Hot-Plug Temperature, Deg. Fahr.
200	2.50	0.0	2.43	0.97	672
170	2.62	5.0	2.45	0.94	670
158	2.67	6.8	2.48	0.93	670
138	2.72	8.8	2.51	0.92	670
100	2.88	13.0	2.57	0.89	668

The foregoing test conditions were: r.p.m., 900; compression ratio, 5:1; fuel used, No. 312; carburetor-air temperature, 70 deg. fahr.; spark, standard automatic; shrouded valve.

It will be seen from the foregoing tabulation and from the curves in Figs. 5 and 6 that both the power and fuel-flow rate increased materially as the mixture temperature was lowered, but that the efficiency was practically unaffected.

Step No. 3-B

(1) This was another supplement to Step No. 3, and was run for the purpose of showing *the effect of mixture temperature on antiknock requirements* of an engine. With the mixture temperatures used in the previous runs, and all other engine conditions held constant, blends of C. F. R. Reference Fuels A-2 and C-6 were made which gave incipient knock at each temperature. From standard calibration curves, the octane-number equivalent of these blends was known. The following tabulation indicates the effect of mixture temperature on antiknock requirement, in terms of octane numbers.

Mixture Temperature, Deg. Fahr.	Antiknock Requirement for Incipient Detonation, Octane Number
100	65.0
138	67.5
158	70.0
170	72.5
200	75.0

The foregoing test conditions were: r.p.m., 900; jacket temperature, 210 deg. fahr.; compression ratio, 5:1; spark advance, 22.5 deg.

While it is well known that increasing the mixture temperature of an engine increases its tendency to knock, it was hardly expected that a 100 deg. fahr. change would be equivalent to as many as 10 octane numbers in the antiknock value required, as shown in the foregoing tabulation.

(2) In the following tabulation, another way of expressing the effect of mixture temperature on antiknock required is shown, in which the compression ratio allowable for incipient knock is shown for the various temperatures, using No. 312 gasoline throughout; that is, the effect of mixture temperature on antiknock requirement in terms of highest useful compression ratio.

Mixture Temperature, Deg. Fahr.	Compression Ratio for Incipient Knock
100	5.65
138	5.50
158	5.30
170	5.20
200	5.00

Table 3—Rear-Wheel Traction—Full-Load Conditions—Pounds

Gasoline Code No.	312 (20 M.P.H.)	352 (20 M.P.H.)	386 (20 M.P.H.)	400 (20 M.P.H.)	432 (20 M.P.H.)	312 (40 M.P.H.)	352 (40 M.P.H.)	386 (40 M.P.H.)	400 (40 M.P.H.)	432 (40 M.P.H.)
Car No. 21	458.0	458.0	462.0	458.0	459.0	418.0	418.0	418.0	419.0	418.0
22	560.0	560.0	558.0	558.0	540.0	525.0	526.0	525.0	526 0	500.0
23	430.0	430.0	446.0	448.0	450.0	336.0	374.0	386.0	394.0	390.0
17	440.0	439.0	438.0	436.0	432.0	400.0	400.0	398.0	400.0	394.0
18	325.0	433.0	428.0	425.0	425.0	385.0	385.0	375.0	370.0	370.0
1	454.0	446.0	443.0	444.0	440.0	412.0	408.0	408.0	400.0	408.0
14	530.0	534.0	528.0	524.0	494.0	509.0	514.0	512.0	507.0	486.0
15	392.0	390.0	394.0	392.0	392.0	380.0	376.0	382.0	380 0	380.0
7	458.0	448.0	440.0	440.0	419.0	446.0	436.0	434.0	426.0	358.0
2	310.0	306.0	310.0	305.0	304.0	276.0	274.0	272.0	273.0	272.0
16	376.0	380.0	380.0	382.0	380.0	364.0	372.0	376.0	366.0	370.0
Average	430.0	438.0	438.0	437.0	430.0	405.0	407.0	407.0	405.0	395.0

It is thus seen that a 100 deg. fahr. rise in mixture temperature required a 10-octane-number rise in antiknock value, or a decrease of 0.65 in compression ratio.

Step No. 4

The last step in this investigation consisted of taking full advantage of both the antiknock and the mixture-temperature characteristics of the more volatile gasolines, thus combining the effects of Steps Nos. 2 and 3. In other words, the *compression ratio and mixture temperature were adjusted to the requirements of each gasoline.* As in all the previous steps, the carburetor was adjusted for each reading, for maximum power, by means of the hot plug.

Effect of Ideal Compression Ratio and Manifold Temperatures

Gasoline No.	Compression (Incipient Knock)	Mixture Temperature, Deg. Fahr.	Power: Horsepower	Power: Increase, Per Cent	Fuel Consumption: Pt. per Hr.	Fuel Consumption: Pt. per Hp-hr.	Fuel Consumption: Lb. per Hp-hr.	Hot-Plug Temperature, Deg. Fahr.
312	5.00	100	3.72	32.5	3.27	0.88	0.64	710
352	4.85	138	3.45	23.0	3.12	0.91	0.68	710
386	4.71	158	3.33	18.7	2.95	0.88	0.68	687
400	4.57	170	3.24	15.5	2.87	0.89	0.70	689
432	4.03	201	2.81	0.0	2.79	0.99	0.77	680

The foregoing test conditions were: r.p.m., 900; carburetor-air temperature, 100 deg. fahr.; jacket temperature, 210 deg. fahr.; spark advance, automatic.

It seems rather remarkable that the power output was increased over 30 per cent with the light gasoline when compared to the heaviest gasoline under these test conditions. If a time should come when much "lighter" gasolines would be commercially available, engine designers, by making full use of the opportunities thus available for increased power, could get either more power from a given sized engine or equal power from a smaller engine. The latter alternative would give the car user better fuel economy; however, it must not be overlooked that this increased performance could be secured commercially only from engines especially designed for the fuel under consideration.

Summary

Probably one of the most important findings in this work has been the serious consequences of too much heat to the intake manifold. A decade ago the expectations of a steadily decreasing fuel volatility induced engine designers to apply a fair amount of excess manifold heat, so as to be on the safe side for the gasoline which might have to be used in their cars before they were many years old. The last two or three years have seen so much vapor-lock trouble as the result of this policy, when using the light gasolines now regularly available, that much of this excess heat has been removed. Also, gasoline refiners have lowered the allowable vapor pressure of gasoline purposely to reduce this trouble, even though it may have reduced the ease of starting in cold weather. There is still, however, a strong temptation to provide excess heat because it reduces the warming-up period for a cold engine. Against this should be balanced the fact that

Table 4—Speed Reached When Accelerating From 10 M.P.H.

Gasoline Code No.	312 (After 16 Sec.)	352 (After 16 Sec.)	386 (After 16 Sec.)	400 (After 16 Sec.)	432 (After 16 Sec.)	312 (After 14 Sec.)	352 (After 14 Sec.)	386 (After 14 Sec.)	400 (After 14 Sec.)	432 (After 14 Sec.)
Car No. 23	37.8	39.3	39.8	40.3	39.0	35.5	37.0	36.5	36.8	35.8
14	45.5	44.8	44 5	45.3	44.3	41.0	41.3	41.8	41.0	40.8
8	37.5	37.5	37.5	36.0	36.8	34.8	34.3	34.3	33.3	33.5
15	34.8	33.5	35.0	35.0	34.5	32.3	31.3	32.0	31.5	31.8
7	37.0	38.0	38 0	37.3	37.0	33.3	34.5	34 5	34.0	33.0
2	31.0	30.8	30.8	30.8	30.5	28.0	28.0	27.5	28.1	28.8
16	33.0	33.0	34.8	34.0	33.8	30.8	30.5	31.3	30.8	31.0
Average	36.7	36.7	37.2	37.0	36.6	33.7	33.8	34.0	33.7	33.6

raising the mixture temperature in an engine 100 deg. fahr. above the minimum required for good distribution may produce a power loss of about 13 per cent and raise the antiknock requirement about 10 octane units.

A second point of considerable interest in this work was that motor cars, as we find them on the road today, are not particularly sensitive, in regard to power, economy or acceleration, to changes in fuel volatility as represented by varying the end point over the range covered by these experiments. In greater detail, our tests indicate the following:

(1) The lower the volatility (or the higher the end point) the greater the mileage per gallon. This checks the C.F.R. data of 1923 with gasolines of much higher end point. However, the gain in mileage from gasoline of low volatility is too small to warrant much compromise with other important characteristics not covered by these tests, such as ease of starting and the like.

(2) With gasolines of about the same volatility as the better grades of motor gasoline now on the market, acceleration and power developed on typical motor cars are a maximum, with carburetor adjustments as used by their owners. Either higher or lower volatility causes a small loss which, as mentioned before, is probably too small to be noticeable to average car drivers.

(3) The initial carburetor setting of a car may alter the effect of changed volatility;

(a) For lean mixtures, the more volatile the gasoline, the higher the mileage per gallon.

(b) For rich mixtures, the more volatile the gasoline, the lower the mileage per gallon.

(c) With an optimum mixture for each gasoline, the more volatile a gasoline, the less the mileage.

(4) Both power and fuel economy can be increased noticeably with increased gasoline volatility, if an engine is designed for that particular fuel, so as to have the least manifold heat necessary for manifold distribution and the highest compression ratio possible without detonation.

Conclusions

In the parallel development of engines and gasoline, we find that volatility of gasoline now available gives the best performance in the cars on the road as they are new adjusted. This situation may be changed at any time in the future. It is my opinion that the design of engines must follow the gasoline which the oil companies find they can market most economically and, judging from the last decade, anything might happen in the next. In the meantime, when exceptional engine performance warrants a more expensive gasoline and an engine designed for it—such as in aircraft service—the more volatile the gasoline, the better the performance.

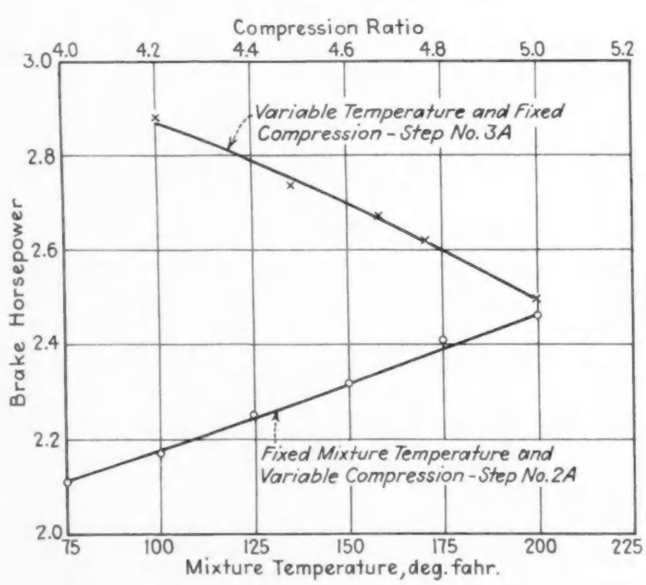

Fig. 6—Power Output as Affected by *(a)*, Compression Ratio and *(b)*, by Mixture Temperature

Discussion

Radical Changes Probable in Fuel-Induction Systems

—**H. F. Huf**
Atlantic Refining Co.

MR. MACCOULL points out that during the last ten years gasoline end points have gradually been lowered in contrast to the increase that had been expected. It would be interesting to know to what extent this decrease in end point was deliberate, in order to obtain improved engine operation, and to what extent the lowering of end point was incidental to improvement in octane number of the gasoline. Low-end-point gasoline is basically less economical than high-end-point gasoline; first, because the high-end-point gasoline has greater heating value per gallon; second, because the yield from crude of low-end-point gasoline is less than that of high-end-point gasoline.

The ideal engine would be so designed that it could use heavy fuels and give all the advantages in performance of both light and heavy fuels. Cold carburetion, but with the fuel atomized to a mist, combined with that distillation curve which would allow enough actual vaporization for ignition, would be a step in the right direction; however, manifolds will have to be capable of handling non-lornogeneous mixtures in order to get proper distribution. There is little doubt that the whole fuel-induction system of the gasoline engine will undergo radical changes, resulting in new standards of performance and permitting wider variation in fuel volatility than at present.

Provision of Riding Comfort

AUTOMOBILE riding comfort is dependent largely on the use of suitable springs in the seat cushions. The first requisite for a good cushion spring is a generous quantity of wire. A cushion spring, if starved for wire, is thereby ruined.

If there is a hidden mystery in the construction of the individual coiled springs that are used in constructing a seat cushion, it lies in the winding of the spring itself. A spring properly wound can be made, utilizing the principle of the shock absorber, that will not strike bottom when loaded and subjected to shock.

—From a 1933 Annual Meeting paper by F. R. Atkinson of the Atkinson Spring Co.

Varied Ideas on Factory Equipment Buying Aired in Discussion of Geschelin Paper

PRODUCTION, general executive and accountant viewpoints are all represented in the discussion presented here, which followed the paper by Joseph Geschelin, engineering editor, *Automotive Industries*, at the International Automotive Engineering Congress in Chicago. Entitled "Executive-Factory Liaison Clears Moot Points in Equipment Buying," the paper was published in the September, 1933, issue of the S.A.E. JOURNAL, pages 23-30 inclusive.

Mr. Geschelin sketched the entire boundary of a factory equipment buying policy, stressing particularly the need for close cooperation between manufacturing and general executives.

"When the top executive," he said, "comprehends more of the manufacturing problems and when the factory executive gets a better vision of broad fiscal problems of the company, we shall have reached a common meeting ground.

"From this it is but a step to the development of the equipment policy."

Accounting Now Big Part of Production Man's Job

— F. W. Cederleaf
Olds Motor Works

BEFORE the depression, the production man's job consisted mainly of a decision on the processing of a part and the choice of the equipment that was to be used; but during the last three years he has found that the study of accounting becomes more and more a part of his job.

Mr. Geschelin's paper states very clearly the things that we production men have known about for a long time; but up to date we have had very little success in presenting our problems to the accounting department. We have not had much to say about the actual factory burden, but still when the factory cost of an article exceeded the estimate, we were held responsible.

As I see it, we must find some way to present this problem to the accounting departments, so that they will realize that this phase of cost is of just as much importance as direct labor. Mr. Geschelin's paper is just a start, and it will be only by continuous discussion of this problem that it will finally come to the attention of management and proper recognition made of it.

Replacement Policies Are Due for More Attention

— By W. H. Rastall
Chief, Machinery and Agricultural Implements Division, Bureau of Foreign and Domestic Commerce

TABLE I in Mr. Geschelin's paper reflects the experience of 23 important companies, illustrates dramatically the absence of an equipment policy even among some of our most important and up-to-date manufacturers. Certain inconsistencies of management also stand out conspicuously.

In recent months under the National Recovery Act in this country, and under more or less similar measures in other countries, there appears to be more and more of a tendency to control industry. These measures will have the effect of emphasizing the factors of excess capacity, technological unemployment, technological progress, depreciation and obsolescence accounting, definite plans for machinery replacement, and in other ways will tend to emphasize this entire subject of an adequate equipment policy in contrast to the indifference with which these subjects have been treated heretofore.

We appear to be entering an era where competition will be upon a different basis, for with prices somewhat stabilized through more uniform accounting, greater emphasis will be given to the factors of quality and service, and there is reason to believe that efficiency and modern equipment will be more and more desirable than heretofore. Also, these subjects will perhaps be considered in terms applying to the industry as a whole rather than to individual establishments.

It would seem that Mr. Geschelin's article is peculiarly timely because of these present trends, and that it will be necessary to revise accounting practices to express more adequately these new conditions and take steps to coordinate

Table 1

1	2	3	4	5	6
Type of Manufacturer and Key No.	Yearly Depreciation Rate, Per Cent	New Equipment Must Liquidate in Years	Is Equipment Formula Used	Sinking Fund (Earmarked)	Book Value Existing Equipment Per Cent
Passenger Cars					
3			No		
5	Gov't Rate	2	No	No	
9	8			No	37
13	..	¼	No	No	Dep. monthly charged to mfg. expense
16	10	2-5	No	No	100 less dep.
17	10	1	No	No	100 less dep.
18	10	3-4	No	No	
20	Gov't Rate	1	No	No	100 less dep.
Motor Trucks					
4	10	1-5	No	No	100 less dep.
10	10	1	No	No	100
12	7½	2	No	No	100
Aircraft Engines					
2	10		No	No	100 less dep.
23	10		No	No	100 less dep.
Vehicle Parts					
1	8½-10	2	No	No	100
6	12 on st'd	1	No	No	20 or second hand value
14	10	50% of dep. rate	No	No	33
Stock Engines					
8	8 on St'd 30 on Spec.	3	No	No	100 less dep.
15	10		No	No (but has general fund)	100 less dep.
19	7½		No	No	49
22	7½		No	No	40
Tractors					
7	10	1-5	No	No	100
11	10	5	No	Yes (normally)	Depreciated
21	5-7½-10	2	No	No	100 less dep.

The above table, referred to in Mr. Rastall's discussion, appeared as Table 1 in Mr. Geschelin's original article published in the September issue of the S.A.E. JOURNAL.

management, accounting, engineering and production management in order that these new conditions may be met in the best possible way.

The suggestion that a separate equipment replacement fund, ear-marked for the purpose, be established and made available to those responsible for shop management, is also most timely because the experience of recent months indicates that all-too-frequently those responsible for the financial management of an enterprise veto the plans for the replacement of machinery advocated by the shop managers because of the pressure experienced when business is depressed, as in recent months, with the result that we have experienced a virtual paralysis of equipment buying.

There is reason to believe that this one factor alone accounts for about three million of those now unemployed in the United States, with parallel conditions in other countries. It would seem that we cannot recover from the present depression until these millions are again at work, and since the policies suggested by Mr. Geschelin indicate the direction in which this might be accomplished, his paper is also peculiarly timely from this point of view.

Data Usually Available; Need Better Presentation

— R. E. W. Harrison

Secretary, Machine Shop Practice Division, American Society of Mechanical Engineers

THERE must be some adequate reason why the business executives of this country have not defined or set up equipment-replacement policies to a greater extent than they have done. A speculative search for these reasons indicates that the following facts might provide a clue.

Based on many years contact with the manufacturing industries as a machine tool engineer, I have had ample evidence that the actual users of production equipment as a whole have a very lively realization of the principles on which replacement should be arranged. In very few instances have they the power to scrap obsolete, and purchase new equipment. They must take all such action in the form of a recommendation to the higher executive, these recommendations being supported to a greater or a lesser degree by evidence based on the individual demands and resources of the case.

Frequently the evidence is inadequate, and not presented in such a way that the imperative need for action is brought out, largely because of a faulty liaison, between the factory executive and the cost recording department. It will be readily conceded that the need, or otherwise, for new equipment is plainly indicated by cost records, providing that these records are made to show cost trend per piece (history) and competitive figures.

The final decision regarding purchasing new equipment must, of course, be determined by someone possessing a complete financial picture of the concern's activities, as equipment replacement must take its place in the line-up of spending mediums, like advertising, sales expense, etc.

It might be said that accurate, comparative running-cost data are the perpetually operating thermometer recording the economic health of a factory, and while it is realized that all cost records are relative, it is in the provision of these data in such a form that it can be used and understood, where the remedy lies.

Wise, far-seeing, conservative management has at its fingertips all the implements and vehicles required to take care of the different activities which go to make up direct and indirect cost, and only awaits the presentation of the case in an understandable way to enable it to take action. Such items as book values of existing equipment, standard and accelerated depreciation rates, and sinking fund allotments

and all the other paraphernalia of management usually stand immediately available for action when the true figures are put forward in such a way that the necessity for this action is apparent.

Specialized Tools Could Have a Special Account

— J. E. Andress
President,
Barnes Drill Co.

ONE of the most outstanding revelations is the fact that only one out of the twenty-one manufacturers in the automotive field has adopted a cash, ear-marked replacement-fund. This constructive suggestion of Mr. Geschelin's is very timely, and needs widespread recommendation.

Boards of directors, particularly in the larger organizations, have seemingly overlooked the profit possibilities of a sound policy of machine-tool replacement.

The desire to conserve liquid funds (frequently beyond all reasonable needs) has caused the sacrifice of much larger operating profits that could have been secured by a proper modernization policy. Many instances could be cited to show the appalling price that manufacturers are paying by restricting funds for better equipment.

Tremendous advances have been made in the design and productive capacity of our present-day machine tools, so that these modern machines have many times the earning power of mere interest on cash reserves.

If Mr. Geschelin's paper can be brought to the attention and consideration of high executives in control of exchequers, it will have served a useful purpose, and I believe will benefit both users and producers of machine tools. Most production engineers appreciate the true value of cost-cutting equipment, but frequently cannot secure the necessary appropriations for purchase because of the short-sighted attitude of management. It would seem, therefore, that top executives need a better understanding of the value of machine-tool investments, and that Mr. Geschelin's proposed ear-marked, liquid fund equipment policy, if adopted through advocation of auditors and accountants who may be convinced of the soundness of the plan, and set up better accounting methods, will solve a problem that has always been a besetting one.

The plan of setting apart actual cash reserves for replacement fund, safeguarded by protective rules, yet to be dispensed at the discretion of, perhaps, in large organizations, the vice-president in charge of manufacturing, without the delay of getting action by the board, will result in millions of increased profits for the stockholders of automobile and other plants.

One other comment. It seems inconsistent to demand that new equipment must pay for itself in 90 days to one, two, or three years, while depreciating at an average rate of around 10 per cent. Highly specialized production equipment must quickly liquidate the purchase price, but should not such specialized machines be carried in an account separated from standard machine tools?

Is 10 per cent an adequate depreciation on standard machine tools in an automobile plant? Admittedly, any machine tool with reasonable care has more than 10 years of useful life, but not for the high production plant, because of the rapid advance in the designs of machine tools, meeting the greater demands of the more durable cutting tools now available. Hence, from the standpoint of obsolescence alone, a machine tool, while having perhaps considerable utility value for the small user, such as repair shops, should and could be profitably replaced easily upon a five-year basis of productive life and adequate earning power.

The conclusions to Mr. Geschelin's article seem to be logical and well drawn.

Proposes Budgeting Replacement Account

— Robert S. Drummond
President,
National Broach and Machine Co.

IT would be of great advantage to production men if there could be set up for the replacement account a definite percentage, as is done for other budget items such as advertising. In these days the advertising program is reduced but not wholly eliminated, and the same thing would take place in the handling of this account.

The principal importance of setting up this item as a budget based on a percentage of manufactured parts is that it would bring it regularly to the attention of the management.

Cash Reserve for Tool Buying Not Justifiable

— J. E. Padgett
Assistant General Manager,
Spicer Manufacturing Corp.

THERE are many good points in the paper by Mr. Geschelin regarding equipment purchase policies. I cannot agree with some of the details and individual policies.

It is true that the welfare of the company is greatly influenced by a proper policy in the purchase of equipment. The statement that the capital goods industries are the "bed rock" of our economic structure is very broad. I believe that consumption goods are the "bed rock" and that capital goods are needed only as a means of producing consumption goods.

Mr. Geschelin brings out strongly a desire for a separate cash reserve which is kept intact for the use of plant management in the purchase of equipment at its best discretion. From the viewpoint of the operating division this would be fine, but it is very seldom that any business has sufficient liquid cash to allow itself to tie up any such amount for one specific purpose. The capital of a company is invested mostly in plant, equipment and inventories. The small balance which is liquid must be mobilized first for one thing and then another. It may be needed for more inventory for a period; again it may be needed to finance credit for a time. The small amounts of liquid cash probably earn 10 per cent per month or more in a properly managed business and must do so if a reasonable return on the entire capital is to be

earned during the year's business. It is, therefore, almost impossible to consider tying up any large amounts awaiting possible machinery replacement needs.

Mr. Geschelin's thoughts on depreciation are very useful. There are many ways of handling this. Without going into any special setup of depreciation it probably would be extremely simple to use a proper average depreciation rate for standard equipment, to charge off special equipment on the actual job which it is purchased to do, either over a given quantity or given period of time.

Obsolescence can be taken care of by writing the machine down to its resale value whenever it becomes obsolete and is used no longer. If this is done regularly there will be no major accumulations at any time, but these write-downs will come regularly and will be found to average a certain amount per year, which can be added to the regular depreciation.

Of course, the whole question of depreciation depends on the spirit behind a given company. Many companies are operated purely from the standpoint of developing the largest possible temporary earnings so that stock promotion can be carried out and the stock unloaded on the public at high prices. In these cases the managements will naturally charge off for depreciation and obsolescence the very minimum they can get away with. Other companies will be operated on

Warner & Swasey Equipment Replacement Statement

Average former cost, 34.0 minutes (per piece) x 2½¢ 850
(with direct labor at 60¢ and overhead at 90¢, a total of $1.50 per hour, or 2½¢ per minute)

Average cost with new equipment 23.5 min. (per piece) x 2½¢ . . . 587

Savings per piece 263

Production per month with new equipment:

$$\frac{\text{60 min. (per hr.) x 9 hrs. (per day) x 23 (working days)}}{\text{23.5 minutes per piece (with new equipment)}} = \text{528 pieces}$$

Total savings per month will then be:

528 (pieces per month) x .263 (savings per piece) . . . 138 86

If the new equipment is kept busy only 80% of the time, deduct 20% for idle time . . . .

20% of 138.86 (Savings per month) . . . 27 76

Value of usable savings per month 111 10

Investment in new equipment 2 745 00

Less resale value of old equipment 300 00

Net cash investment in new equipment 2 445 00

The new equipment will pay for itself in:

$$\frac{\text{2,445 00 (Net cash investment)}}{\text{111.10 (Usable savings per month)}} = \text{22.0 months}$$

The Net Profit return per year will be:

111.10 (Usable savings per month) x 12 months . . . 1 333 20

Less 20% depreciation on 2,445.00 (Net cash investment) . . . 489 00

Net Profit per year after depreciation 844 20

The rate of Net Profit will be:

$$\frac{\text{844.20 (The Net Profit)}}{\text{2,445 00 (Net cash investment)}} = \text{34.5\%}$$

The above statement, referred to in Mr. Padgett's discussion, appeared as Fig. 3 in Mr. Geschelin's original article published in the September issue of the S.A.E. JOURNAL.

the basis of policies that will keep that company as a going business steadily over a great many years and their policies will be extremely conservative so that at all times the true values are as near as possible to the values shown on their books with perhaps some little extra to take care of emergency conditions.

I do not think it is very useful to use a formula for arriving at machinery replacement needs because no formula can take the place of good judgment. A formula usually is based on past conditions, taking into account nothing regarding the future except that the future is supposed to be the same as the past, whereas in reality the future is vastly different than the past.

I am very much interested in the example of the Warner & Swasey Equipment Replacement Statement. This is quite similar to the way many people calculate the savings from new machinery. To my mind it is entirely incorrect and I am attaching the conclusions I would reach based on exactly the same sort of facts:

Average former cost 34.0 minutes per piece at 60 cents per hour direct labor		$0.340
Average cost with new equipment 23.5 minutes at 60 cents		0.235
Direct Labor Saving		0.105
Production per month		365
Savings per month .105 times 365		38.33
New Investment	$2745.00	
Sale of Old Equipment	300.00	
	$2445.00	
New equipment will pay for itself in 63 months.		
Net profit per year will be		
Savings		459.96
20 per cent per year sinking fund		489.00
LOSS		$29.04

In explanation of the above table, I think it is a fallacy to include overhead in the costs per piece that are used to determine savings.

A department has certain equipment, foreman, inspectors, tools, power, etc., and I cannot see how the addition of a machine can reduce any single one of these items. As a matter of fact it increases them. The only true savings are savings in direct labor and this is all that should be considered. Of course, there are exceptional cases which must be taken into consideration, but on the average a replacement machine does not save burden.

In the next place it would be assumed that the present equipment can produce all of the necessary pieces since this is a replacement matter and not equipment for expansion. Therefore, the monthly production must be figured on the former machine and not the new machine. With these two changes in viewpoint the balance of the calculation is exactly the same as that shown, but it results in showing a net loss by purchasing this equipment instead of a very handsome profit indicated in Mr. Geschelin's table. It is just such misconceptions that have resulted in an over-abundance of equipment which built up the machine tool industry to the heights and has now caused it to drop into a deep valley until normal wear and tear have used up equipment purchased wrongly during previous times.

Mr. Geschelin also brings out the fact that most manu-

facturers require new equipment to save its purchase price in approximately one year. He claims that this is not a proper thing. I believe it is entirely correct. We are not talking about the necessary equipment to carry on a business but are talking about equipment purchased, which, by savings, can make itself valuable. To produce a proper return on this investment which is not a necessity, it must pay for itself in about a year or we merely transfer losses of direct labor into losses on the burden side of the picture.

The last item is the question of price which Mr. Geschelin says has been greatly over-emphasized. Price in itself means nothing, but a given price level may make it uneconomical to purchase a given machine at all.

Proves Cooperation Can Solve Accounting Task

— **Clinton Brettell**
Garage Superintendent, R. H. Macy & Co., Inc.

THE question of ear-marking depreciation replacement funds is a matter that I have personally encountered in various connections when endeavoring to secure appropriations for the purchase of shop equipment. Very often the answer that no funds were available was given, although equipment was written off the books and new funds, therefore, presumably available. It seems questionable, however, whether cash obtained from depreciation of equipment items could be definitely segregated. The budget method seems, actually, to be solving the problem very well in the organization with which I am connected. All departments are required to announce for periods in advance what their anticipated expenditures will be and if those expenditures can be justified, appropriations are set aside from the funds of the business so that purchases can be made when needed.

Mr. Geschelin's statement regarding an apparently high salvage-value in semi-automatic machinery was quite a surprise, as it seemed possible that the lower parts of the machine, although representing a very considerable proportion of the total on a weight basis, would not entail any great amount of design or machining, so that, from a cost standpoint, they would not represent such a high percentage of the total as the 50 to 75 per cent mentioned by Mr. Geschelin.

The depreciation formula submitted by Mr. Geschelin was very interesting and apparently necessary, as there certainly are wide variations in the rate at which equipment wears out or becomes useless from obsolescence. Also, there is a considerable difference between the useful-life depreciation and the accounting depreciations which exist in most companies.

I disagree very strongly with previous speakers who have expressed the opinion that accounting matters should be left strictly to the accountants. As an example of what can be done by coordination of these various interests, I would cite an experience in connection with automotive depreciation and replacement in our organization. Originally, there seemed to be no uniform method of replacement, and it was done largely on a hit or miss basis.

Realizing that such a method would ultimately result in high costs and inferior operation, and that blame for such condition would finally ride on my shoulders, I presented the matter to the store economist, and to the accountant and delivery superintendent, who were convinced that some logical plan should be developed. By a joint study of the matter by these various divisions, a logical, mathematical basis was arrived at and presented to the management in a way so convincing that it was adopted for the future. This is an example of what can be done by cooperation, and it seems incumbent upon the operating men themselves to take the initiative or suffer the consequences.

Regarding the matter of prices of machinery, the point mentioned by Mr. Geschelin regarding free engineering service as being one item leading to increased costs and which he attributed to the purchaser, in my opinion, is a matter that is entirely in the hands of the seller, as the purchaser will always get all the free service he can, provided one seller or another is willing to offer it.

Accounting Is Not Basis For Equipment Selection

— **Max Sklovsky**
Chief Engineer, Deere and Co.

IN his conclusions Mr. Geschelin falls into the error of covering too large a territory for a production man. While it is desirable that all branches of the business—the production branch, the sales branch, the financial branch—should cooperate through mutual understanding, it is intolerable that one branch should dictate or interfere with the work of the others. There are reasons for certain accounting practice which the production man may not understand, or which he has had no time to study. There are reasons why the financial man cannot understand the production problems. They must therefore respect each other's fields and not upset each other's plans.

The endeavor to change the entire plan of operating in business to conform to the notions or necessities of a department can hardly be considered acceptable.

The operating department must solve its problems in its own way and can use a sub-accounting plan of its own sufficient for the immediate needs and sufficient for the problems at hand. The operating policy of the factory does not require the disturbance of the financial auditing or accounting policies, no more does the accounting policy require changes in fabricating methods. There is never time enough for one group to re-educate other groups its own ideas.

The selection of equipment is not based upon accounting, it is based entirely on material results and upon material facts. In the customary accounting with labor as a denominator, there is an average factory overhead, including all other expenses, which usually is 200 per cent or 300 per cent of that of direct labor. On some equipment of the automatic type the accumulated overhead of tool expense, depreciation, maintenance and power may run as high as 1000 per cent over labor. In some instances, tool expense alone amounts to 600 or 800 per cent. On the other hand, assembly work,

where no machinery is used, where little power is used, the principal is that of direct labor, and the total overhead in that case ranges from 40 to 60 per cent. A labor-saving device affects, in the latter case, the direct labor alone, whereas, in a complex machining operation, all the items of overhead may be seriously disturbed and may increase or decrease. Mr. Padgett emphasizes this very effectively in stating that the overhead burden cannot be taken into account as a saving and making comparisons between one type of equipment and another in case of replacement. Usually most of the overhead of the old equipment remains.

The classification of the depreciation ratio for each type of machine becomes too complex. For practical purposes, therefore, a division of equipment into three groups serves the purpose adequately. These three groups can be roughly designated as (1) Permanent Equipment, (2) Ordinary Equipment for rough work, and (3) Precision Equipment. Precision equipment deteriorates very rapidly.

Limiting Factors in Headlamp Design

POINTING out that an engineer for one car manufacturer figures the wind resistance of the headlamps on his car at 50 m.p.h. amounts to 5 hp., W. C. Brown and V. J. Roper, in a paper presented to the Illuminating Engineering Society, contend that headlamps offer the chief impediment to further efforts toward cleaning up the front of the car in the interest of better styling and improved efficiency.

The small dimensions possible in a multi-unit system give the car designer a freedom he has never before enjoyed and permit him to realize the ideal lines for which he has been striving.

A multi-unit system of headlamps ordinarily would comprise four units, each with a different light distribution. The main driving beam for the open road, the meeting beam, and the lower beam for city use would each be formed from two units, or in some instance from three. Since only two units are used to produce the main driving beam, limitations as to vertical concentration do not apply with equal force to the other two units, and one or both of them might therefore be made of even smaller diameter if desired.

Any consideration of motor vehicle headlamp design must proceed from the type of beam that is to be provided, and especially the candlepower gradient that is required at the top of the beam. At present, the aiming restrictions in many of the States require a sharp cut-off of the beam at or below the horizontal. This necessitates a sharp gradient at the top of the beam, and for satisfactory uniformity of road illumination, a high-intensity portion at the top that is not over 2 deg. in vertical depth.

For the lower beam of two-beam equipments, the upper part including the high-intensity portion, is depressed so that the upper cut-off is lowered about 2 deg.

A much more desirable meeting beam has been provided by maintaining the light on the right-hand side of the road at or even slightly above the horizontal to provide light down the driver's side of the road. The left side is depressed as before. This is accomplished by providing an asymmetric distribution from each headlamp, one lighting the right side of the road and the other the left.

The headlamp should intercept 65 per cent or more of the light from the source and redirect it ahead in a beam of suitable pattern. The alternative is sources of higher candlepower than heretofore used and a consequent increase in the size of the electrical system. The headlamp should be fixed-focus. In a multi-filament unit the angle of tilt between the tops of the driving and lower beams should be maintained throughout the range of the variations encountered in the manufacture and assembly of the various parts.

Present-day headlamps usually are 8 to 10 in. in diameter or larger. The reflectors are paraboloidal or modified contour, of relatively long focal length (1 9/16 to 1¾ in.) intercepting 60 to 70 per cent of the light from the lamp. They are large because with the long focal length a considerable diameter is required to provide adequate utilization.

In the multi-filament system, two or more sources are included in each lamp to produce more than one type of beam with the same optical elements. The driving beam's light source is substantially at the focal point while the source for the lower beam is displaced from the focal point. The efficient way of producing the tilt, which is necessary when a shift is made to a source displaced from the focus, is by placing the second source above the focus.

A system now in vogue on a number of cars produces an asymmetric meeting beam by using a lens or reflector contour modification which directs the major portion of light to one side of the road. Or the high-intensity part of the beam may be shifted to the right as well as (or instead of) downward. A third source may be added in one lamp to provide for the city lower beam.

Physical tolerances in the manufacture of lamps, sockets, and reflectors, and in their assembly therefore constitute one limit to size reduction. Moreover, as the focal length is decreased, the filament images from a given section of the reflector become larger. Therefore less reflector area is available to produce images of a size small enough for the high-intensity portion of the beam.

For two-filament operation, the high-intensity portion of the beam must be formed from the side sections of the reflector but when only one beam is to be provided from each unit in a multi-unit system, the high-intensity portion at the top of the beam may be formed by using also upper or lower zones.

When State regulations with reference to intensities above the horizontal are modified for the main driving beam, some reduction in the limiting diameter and focal length of the headlight units becomes feasible, for the critical part of the beam, from the standpoint of fixed focus characteristics, is this high-intensity section, so far as the multi-unit system is concerned.

As the units become smaller, their brightness increases, since the candlepower must be maintained at the same values as those obtained from large headlamps. Higher brightness means additional glare.